DETERMINATION OF CONSISTENCY LIMITS OF SOILS BY MOISTURE - TENSION METHOD

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Final Report

DETERMINATION OF CONSISTENCY LIMITS OF SOILS BY MOISTURE-TENSION METHOD

TO: J. F. McLaughlin, Director
Joint Highway Research Project

February 8, 1973

Project: C-36-5K

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-6-11

Attached is a final report covering the research carried out by Mr. Atef Gadallah during the past year on predicting liquid and plastic limits of soils using the moisture-tension device. The research was conducted in two basic parts. First, a series of tests was made on 38 soils for the purpose of establishing prediction equations for both the liquid and plastic limits. The results of these tests showed very good correlation between the standard test results and the moisture-tension test results.

The second part of the research dealt with checking the mathematical model discussed above using a total of 144 samples selected in a randomized manner. The results of this series of tests showed good correlation for the liquid limit and fair correlation for the plastic limit.

The research indicated that the moisture-tension device shows good promise for predicting the consistency limits. Additional research should be conducted to further check this out. We will submit a work plan on this in the future.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

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by

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Graduate Assistant in Research

Joint Highway Research Project

Project No.: C-36-5K

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ABSTRACT

Gadallah, Ahmed Atef. M.S.C.E., Purdue University, December 1972. Determination of Consistency Limits of Soils by Moisture Tension Method. Major Professor: E. J. Yoder.

This thesis presents the results of a laboratory investigation of the relationship between the consistency limits and the moisture content as obtained by the moisture tension method.

Thirty-eight soils from Indiana were used in this investigation. The ceramic plate apparatus was used for the moisture tension method. The effect of method of preparation of soil samples on the moisture tension method results was evaluated. The reproducibility of both the standard ASTM test and the moisture tension method results were studied.

The results of this investigation indicated that a linear relationship exists between the consistency limits (LL and PL) and the moisture content, WC_i, obtained at various pressure intensities, (6, 10, 12 and 18 psi). The results of the study strongly suggest that the moisture tension test can be used on a routine basis for determining the consistency limits of soils.

INTRODUCTION

The Atterberg Limits have been extensively used for identifying engineering properties of soils and specifying quality of base courses. Almost all specifications for base course materials set some limits on these constants. In order to get consistent test results for the liquid and plastic limits and to minimize the time required for such tests, attempts have been made either to modify the standard method for determination of these limits or to correlate the limits obtained by the standard method with those obtained from a completely different method.

The moisture tension method (11, 15, 16)* has been studied as an alternate procedure for estimating the liquid and plastic limit. It appears that this concept provides a feasible method for determining the consistency limits. The results obtained by this method show a higher degree of reproducibility. The method also permits expedition in testing as a large number of soil samples can be tested simultaneously.

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*Numbers in parentheses refer to references listed in the bibliography.

However, there are some limitations relative to the use of the moisture tension method for determining the consistency limits. Most studies have evaluated this technique for estimating just the liquid limit. The use of this technique for the plastic limit determination and for the identification of non-plastic soils has not been fully explored. Also, there is some disagreement relative to the method of preparation of the test samples. Most previous studies have utilized textural classification of soils as a basis for determining the relationship between moisture tension and liquid limit. Generally, a specific pressure intensity was recommended for a given soil textural group.

Further research is needed to investigate the use of a single pressure intensity for the determination of the moisture tension-consistency limits relationships for soils, irrespective of their textural classification. This would result in making the moisture tension method a practical tool for estimating the liquid and plastic limits.

PURPOSE OF THE STUDY

The primary purpose of this study is to establish a relationship that would permit the prediction of liquid and plastic limits by the moisture tension method with the specific objectives of:

1. studying the effect of method of preparation of the soil samples on the results obtained from the moisture tension method,
2. investigating the possibility of using a unique pressure intensity in the moisture tension test for establishing the moisture tension-consistency limits relationship for various soil types regardless of their textural classification,
3. specifying a limit on the moisture content values, as obtained from the moisture tension method utilizing a unique pressure intensity, below which a soil could be classified as non-plastic, and
4. investigating the possibility of speeding up the process by analyzing the time factor effect on the moisture tension test results.

BACKGROUND

Atterberg Limits

Consistency limits were first suggested by A. Atterberg in 1911 as the moisture content boundaries that separate different states of a soil-water system. The liquid and plastic limits were defined as the moisture content at the upper and lower limits of the moisture range within which a soil exhibits the properties of a plastic solid. The soil is said to be in a plastic state when it has the ability to change shape continuously under the influence of an applied stress, and to retain the new shape on removal of the stress. In other words, the plastic limit is defined as that water content below which the soil is not plastic when it is worked, and crumbles on application of pressure. At the liquid limit the change is from plastic to flow behavior. The range of water content over which a soil exhibits plastic behavior is defined as the plasticity index. The plasticity index is defined as the difference between the liquid limit and the plastic limit values.

Since these limits and related indices have proved to be very useful for soil identification and classification,

many investigations have been conducted to relate the consistency limits to other properties of soils. Considerable work has been done to provide theoretical definitions and physical interpretation of these limits.

Grim (8), after a comprehensive explanation and discussion of clay mineralogy and its application to engineering properties, concluded that the Atterberg limits could be explained as follows. The plastic limit, according to Grim, is a measure of the water content slightly in excess of the amount that the particle surface can absorb in a highly rigid condition, without creating a sufficient water thickness between particles to reduce the attractive forces between them. The liquid limit is a measure of the water which can be held by the soil with some substantial rigidity and which does not separate the particles, so that there is substantially no bonding force between them.

Terzaghi and Peck (21) pointed out that the transition zone from one state to another does not occur abruptly as soon as some critical water content is reached, but rather, occurs gradually over a fairly long range of the water content. From this reasoning they concluded that attempts to establish criteria for the boundaries between the different states of the soil involve some arbitrary elements.

Casagrande (4) studied the consistency limits and provided a standard test device and procedure for the

liquid limit determination. The standard test minimizes the variation due to different test devices and operator techniques. Casagrande also suggested that the liquid limit can be defined scientifically as a shear strength, that is, the number of blows required to close a standard groove cut into the soil represents a measure of the shearing resistance of the soil. Thus, the liquid limit could be roughly defined as the moisture content at which a soil has a shear strength of approximately 25 gm/cm^2.

In another study Casagrande (5), indicated that many properties of clays and silts could be correlated to Atterberg limits. He also presented a plasticity chart, in which the fine-grained materials were classified and identified according to their liquid limit and plasticity index.

Seed et.al. (18) examined the physical significance of Atterberg limits and provided theoretical relationships between liquid and plastic limits and the clay content of a soil. In their study, it was indicated that for soils containing a given type of clay having a constant value of W_{cLL} (liquid limit of clay fraction), the liquid limit of a soil is directly proportional to the liquid limit of the clay fraction and the proportion of the non-clay particles. It was assumed that the plastic limit of a soil follows the same behavior as that of the liquid limit.

These relationships are valid only if the non-clay particles are not in contact, that is when the volume of the mixture of clay particles and water is greater than the volume of the voids in the non-clay fractions. In the same study, the relationship between plasticity index and liquid limit for organic and inorganic clays was investigated. Comparing the findings with Casagrande's A-line, Seed concluded that there is a good agreement between the two with minor deviations.

Dawson (6) investigated the reproducibility and the variation in results of the standard liquid limit test and recommended that further investigation be made to delineate the factors that influence the liquid limit test procedure.

Morris et.al. (10), provided some recommendations for changes in the liquid limit test to overcome the operator and equipment variability.

Soil Moisture Tension

Several attempts have been made to develop new devices and techniques that could be substituted for the standard method. In this regard, the moisture tension method offers a new approach for the prediction of both the liquid and plastic limits.

The moisture tension apparatus was developed by Richards (13, 14) for measuring the capillary potential of soils.

Rollins and Davidson (15) investigated the relationship between soil moisture tension and the consistency limits of a soil. They concluded that there is a certain pressure intensity corresponding to each soil textural group which gives, to an accepted degree of approximation, the liquid limit values for the soils falling within each group. The moisture tension pressures they recommended for Iowa soils are those presented in column 1 of Table 1.

Sultan (19), along similar lines, investigated the moisture tension method using Utah soils. The procedure for estimating the liquid limit of soils was also based upon soil textural classification. His results are shown in column 2 of Table 1.

Russell and Mickle (16), indicated that the moisture tension desorption curves (drying curves) follow a certain trend for each soil textural group. They pointed out that the composition of the soil sample controls the parameters that affect the curve shape and suggested that the sharpness of curvature could be related to the silt-clay ratio. Moreover, they studied the characteristics of the moisture tension curves and divided these into three distinct regions, lower flex, upper flex and the unloading region between the flexes. These three regions represent

TABLE I . Soil Moisture Tension Recommended For Approximating The Liquid Limits

TEXTURAL GROUP	MOISTURE TENSION VALUES		
	I	II	III
CLAY	6* (0.22)**	—	40 (1.44)
SILTY CLAY	15 (0.54)	—	40 (1.44)
SILTY CLAY LOAM	60 (2.17)	120 (4.30)	60 (2.17)
CLAY LOAM	—	—	60 (2.17)
LOAM	—	110 (4.00)	70 (2.53)
SANDY LOAM	—	70 (2.53)	70 (2.53)
GRAVELLY SANDY-LOAM	—	—	70 (2.53)
SILT	—	—	70 (2.53)
SAND	—	40 (1.44)	—
SILTY LOAM	60 (2.17)	130 (4.30)	—

I Results From Rollins and Davidson (15)

II Results From Sulton (19)

III Results From Russell and Mickle (16)

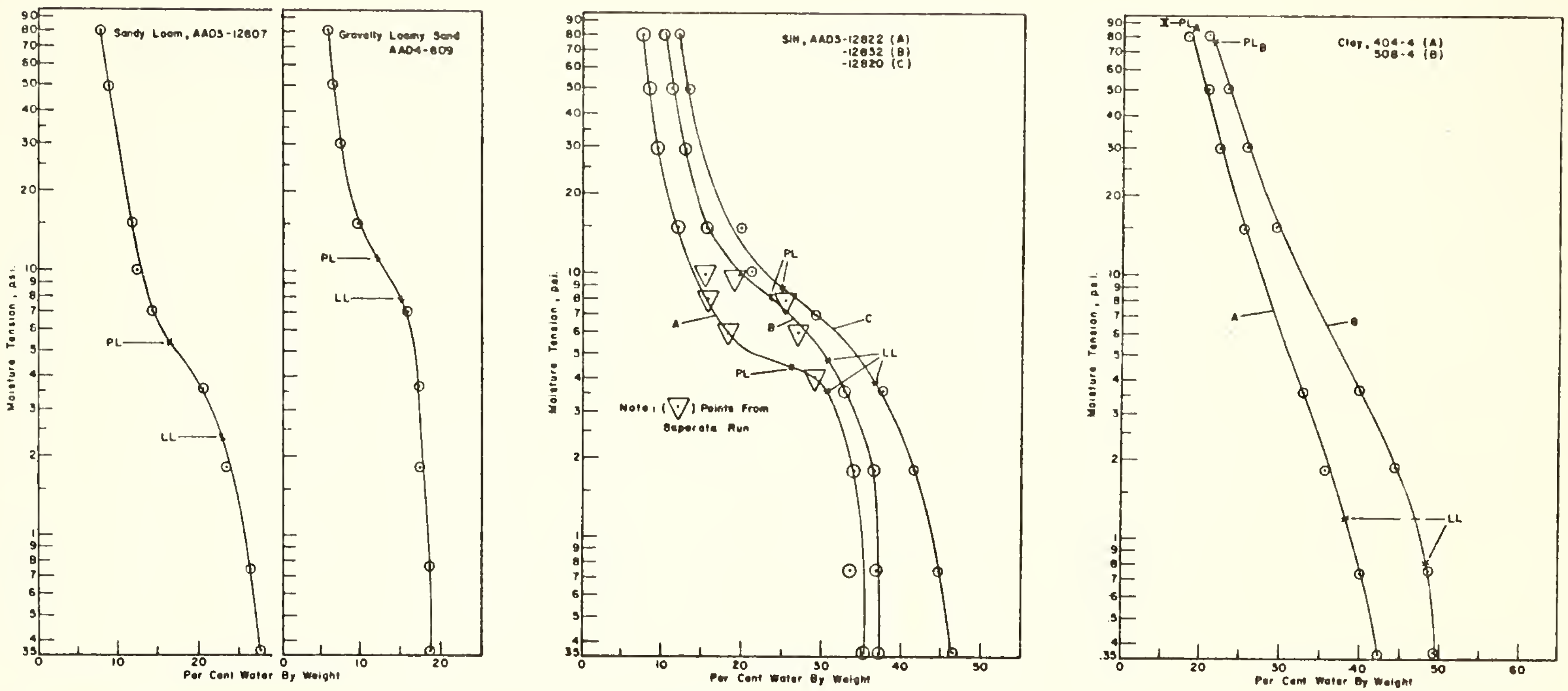
* Soil Moisture Tension in Inches of Water

** Numbers in Parentheses are Soil Moisture Tension in psi

the liquid limit, plastic limit and plasticity index respectively. Figure 1, shows an example of these curves. In the same study it was indicated that the liquid limit could be predicted by using certain moisture tension values which depend upon the soil textural classification. Their results are shown in column 3 of Table 1.

It can be observed from Table 1 that, for some of the textural groups, there is a difference among the results of Rollins and Davidson, Sultan and Russell. Sultan (19) attributed the difference between his results and those of Rollins and Davidson to the probable use of soils with different mineralogical content and geological origin. Later, Sultan (20), pointed out that the difference in results among the three studies could also be attributed to the use of textural classification or the gradation of the material as the governing factor in the determination of the liquid limit by moisture tension method.

Uppal (22), provided a scientific explanation for evaluating the plastic limit by moisture tension method. Uppal's tests were conducted on soils compacted to bulk density of 1.6 gm/cm^3 and with plastic limits ranging from 17 to 34 percent moisture content. He indicated that the plastic limit of soils has physical existence as a definite point on the moisture tension curve under certain controlled conditions. The plastic limit corresponds to



Sandy Loamy and Gravelly Loamy Sand

Three Silts Typical of Group

Two Clays Typical of Group

FIGURE 1 . Typical Moisture Tension Curves (From Russell and Mickle)

the moisture content at PF* 0.5 on the wetting curve or PF 1.5 on the drying curve. The results correlated very closely with the ASTM Standard Test results, and the procedure minimized human error. However, his procedure is not practically usable because a period of 40 to 45 hours is required for the equilibrium moisture content to be reached.

In the same study Uppal pointed out that in testing plastic soils, the moisture contents on wetting and drying curves were widely different at low PF values, such as 0.5 to 0.6. The tests on non-plastic soils, which were conducted using sand samples compacted at a dry bulk density of 1.3, 1.4 and 1.55 gm/cm^3, the moisture content was the same on both curves (absence of hysteresis at a PF value of 0.5). From these results he proposed that non-plastic soils could be identified by utilizing the moisture tension relationship curves.

Livneh et.al. (9) investigated the possibility of correlating soil suction with the plastic limit and the plasticity index. The studies were carried out on 20 soils classified into three groups. The criteria of classification were the grain-size distribution and values

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*PF = logarithm of the tension in centimeters of water.

of the liquid limit. They concluded that in the range of 2 to 4.2 PF (approximately 1.4 psi to 230 psi) a relationship between the moisture content and the corresponding suction value (PF) could be expressed by:

$$PF = a + b \log W$$

where a and b are constants depending only on the soil type, and W is the moisture content. They also suggested another linear relationship between the logarithm of the plasticity index of a soil and the corresponding suction value (PF) and between the logarithm of the plastic limit and the corresponding (PF). However, the correlation between PF and log PI was better than that with the plastic limit. The intersection of the suction curves, obtained by the method used in their work, with the linear relation between PF and log PI gives a predicted value for the plasticity index. However, this method also depends upon soil classification.

Nishio (11) investigated the relationship between the moisture content as determined by the moisture tension method and the consistency limits for Indiana soils. He conducted his research using natural and artificially prepared soils (varying gradation) from the same natural soils. The findings by Nishio show that the values of $(WC_3)^2$, $(WC_{20})^2$ and $(WC_3)(WC_{20})$, where (WC_i) is the

moisture content of the soil sample at i psi moisture tension, are well correlated with the liquid and plastic limits and plasticity index of the soil. These results were shown to be valid regardless of the textural classification of the soils as established by previous researchers. From the analysis of the predicted values obtained by using the moisture tension method, Nishio indicated that the variation between the predicted values were within the variation of the observed values as obtained by the ASTM Standard Method.

In the same research, Nishio studied the relationship between WC_3 and WC_{20} and using a plot between these two factors, he suggested an arbitrary boundary line delineating the non-plastic materials from the plastic materials.

Based on the above study, it can be concluded that it should be possible to apply the moisture tension test using two pressures (3 psi and 20 psi) on a soil to estimate its consistency limits regardless of its textural classification. However, it is noticed that each of the previous researchers used a certain procedure for soil samples preparation. Rollins and Davidson (15), used the procedures outlined in the U.S.D.A. Handbook No. 60 (23), and stated that this procedure must be followed carefully because the moisture tension results are affected by the initial moisture content. Russell and Mickle (16) after

a brief study of the effect of the initial condition on the test results, used a modified version of the procedure used by Rollins and Davidson. Nishio (11), also used a slightly different procedure for the preparation of the samples. Additional attention should be directed to study the effect of method of preparation on the moisture tension results.

EQUIPMENT AND MATERIALS

Moisture Tension Method Equipment

The apparatus used in this investigation essentially consisted of a ceramic plate extractor capable of holding three ceramic plates. Each ceramic plate is approximately 10-1/4" in diameter and of a design permitting the tests to be run in the 0 to 1 bar pressure range. Usually it is designated as the "1 bar ceramic plate". A description of the moisture tension method apparatus was presented in detail by Nishio (11).

Soil samples are placed in rubber rings (2" inner diameter and 1/2" high) on the ceramic plates which are mounted in the extractor. A maximum of twelve soil samples can be placed on each plate. When the pressure is applied in the extractor, excess water from the soil is forced out of the extractor through the ceramic plate cells and the outflow tubes. The flow ceases as the equilibrium moisture state is reached.

Materials

This investigation was conducted using thirty-eight soils obtained from Indiana State Highway Commission. The liquid limit values of these soils ranged from 18 to 50

percent moisture content, while the plasticity index values were less than 21 percent moisture content.

The soils were classified into four groups, using the liquid limit-plasticity index relationship as indicated in the plasticity chart in Figure 2. The four groups are as follows:

1. Inorganic clays of low to medium plasticity, silty clays, lean clays, as indicated by the symbol CL.
2. Inorganic silts and silt clays, as indicated by the symbol ML.
3. Inorganic clays and silts of low plasticity, as indicated by CL & ML.
4. Non-plastic materials, mostly silty sands.

Table 2 shows the plasticity data and grouping of the soils. The portion of the soil passing the No. 40 sieve size fraction was used in all tests.

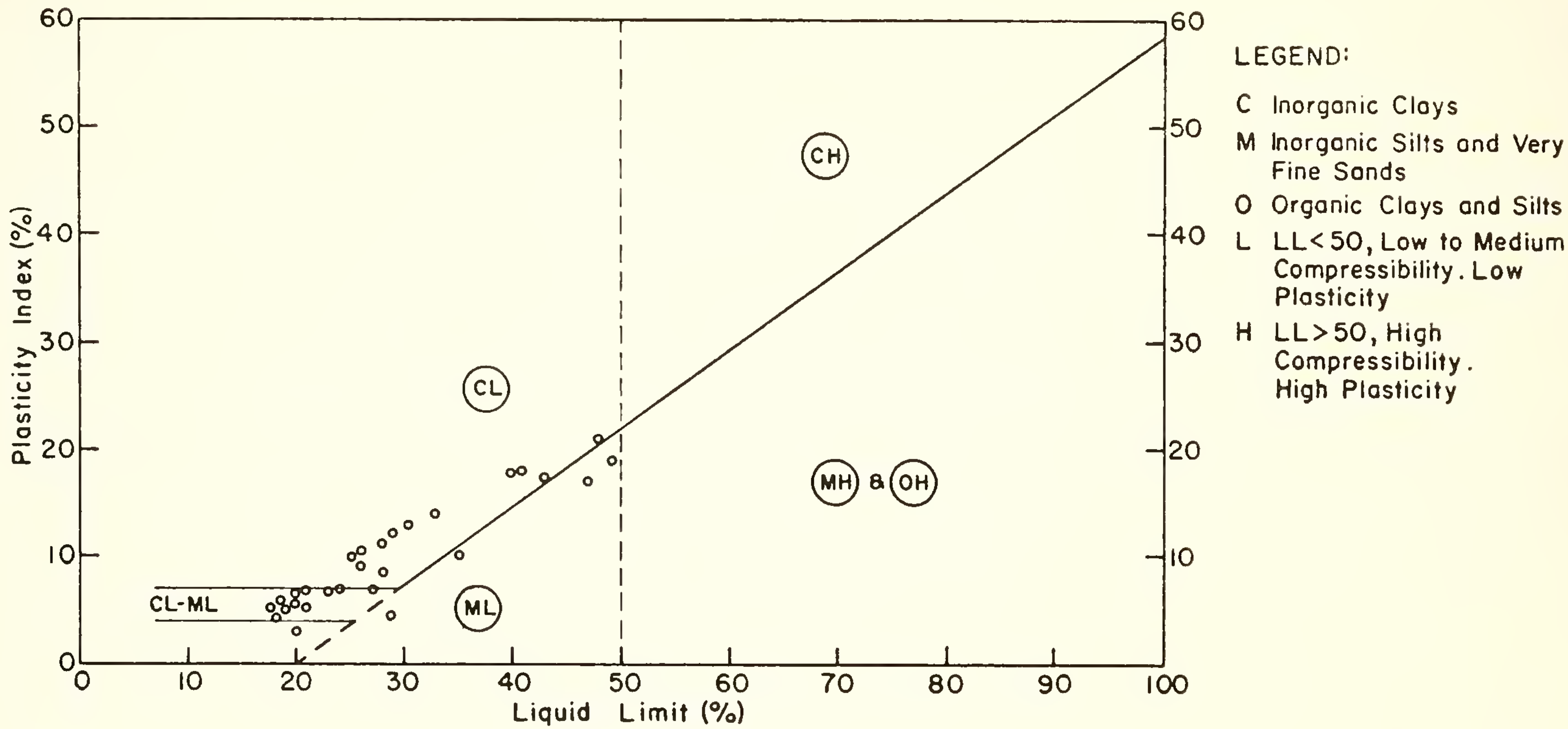

FIGURE 2. Plasticity Chart, Unified Classification of Soils

TABLE 2. Soil Groups As From The Plasticity Chart

SOIL NO.	LL*	PL**	PI†	SOIL GROUP
1	25.6	15.4	10.2	CL
2	25.3	15.8	9.5	
3	42.9	26.5	16.4	
14	48.1	27.0	21.1	
17	40.6	22.8	17.8	
18	39.6	21.7	17.9	
20	33.3	19.5	13.8	
21	26.3	16.3	10.0	
22	27.6	19.1	8.5	
23	30.6	17.8	12.8	
24	28.2	17.1	11.1	
25	28.8	16.8	12.0	
26	26.7	19.1	7.6	
29	24.2	17.2	7.0	
4	28.9	25.1	3.8	ML
19	35.6	24.6	11.0	
33	46.4	30.0	16.4	
34	49.4	30.2	19.2	
5	19.3	14.6	4.7	CL & ML
6	20.1	14.0	6.1	
7	21.6	16.2	5.4	
8	18.5	13.6	4.9	
27	22.5	15.6	6.9	
28	21.1	14.1	7.0	
30	18.9	13.9	5.0	
31	20.3	14.6	5.7	
32	18.9	13.9	5.0	

TABLE 2 , Cont.

SOIL NO.	LL*	PL**	PI†	SOIL GROUP
10	20.0	16.4	3.6	NON-PLASTIC, MOSTLY SILTY SANDS
9	—	—	—	
11	—	—	—	
12	—	—	—	
13	—	—	—	
15	(18.1)††	(15.6)	(2.5)	
16	—	—	—	
35	(19.0)	(16.5)	(2.5)	
36	—	—	—	
37	(18.0)	(16.0)	(2.0)	
38	—	—	—	

* Average of 4 Replicates For The Liquid Limit

** Average of 4 Replicates For The Plastic Limit

† Plasticity Index

†† Values in Parentheses Were Obtained From One Test Only

DESIGN OF THE EXPERIMENTS

The experiments utilized in this research were statistically designed to permit an objective analysis of the factors given below.

Each soil type was first split into as many samples as needed for the entire research. This procedure was carried out to insure the homogeneity of the samples, that is, to have identical representative samples for each soil. The experimental designs for various phases of this investigation are as follows:

A. Study design: effect of method of preparation of soil samples on moisture tension test results. A 3x5x6 factorial design was used in this phase of the investigation. The three independent factors were:

1. replications of experiment, R
2. method of preparation, M
3. soil type, S.

The replications of the entire experiment were necessary to provide appropriate tests for the analysis. The dependent or the measured variable was the moisture content of the soil samples

obtained from the moisture tension method, at 10 psi pressure intensity.

B. Study design: reproducibility of the liquid and plastic limits obtained by the standard ASTM test procedures.

A 28 x 4 completely randomized design was used. The measured variables were the liquid limit and the plastic limit as obtained by the standard tests. The tests were performed on the 38 soils at random to remove the bias introduced by learning effect or the time factor. Ten soils, which were non-plastic, were excluded from the analysis.

C. Study design: prediction of the liquid limit and plastic limit of a soil by the moisture tension method.

A linear regression analysis was used to develop prediction models for liquid and plastic limits. A separate model was evaluated for each of the 6, 10, 12 and 18 psi pressure intensities. Both disaggregate and aggregate data were used in the analysis.

D. Study design: reproducibility of moisture tension method results.

A 4 x 38 randomized complete block design was utilized. Four replications of the tests on 38 soils constituted the blocks. This blocking technique had to be used because of the nature of the experiment. A test utilizing all the 38 samples had to be completed before the replicate test could be run. The dependent variable was the equilibrium moisture content obtained at a pressure intensity of 10 psi.

E. Study design: time factor effect on the moisture tension method results.

A 2x6x5 factorial design was used. The three independent factors were:

1. replications, R
2. time, T
3. soil type, S.

The measured variable was the moisture content of the soil sample at 10 psi. After performing the analysis, Newman-keuls test was run on the treatment (time factor) means. The same design was used for the 18 psi pressure intensity.

TEST PROCEDURES

Standard Tests for Atterberg Limits

The liquid and plastic limits were determined in accordance with ASTM designations, D 423-61T and D 424-59 respectively (2). Four replicate tests were performed on each soil used in this study.

Moisture Tension Test

Each soil sample of 50 grams weight was put into a jar (the portion of soils used was that portion passing the No. 40 sieve fraction). A sufficient amount of distilled water was added and mixed until the point where the soil mass could be slowly poured out of the jar, with care taken that it was not so wet as to have free water on the surface when standing. The samples were allowed to stand in the capped jars for two hours before placing them on the plates.

The ceramic plates were placed in the extractor and wetted with distilled water prior to placing the soil samples on the plate (see Figure 3). Twelve rubber rings of 2" inside diameter and 1/2" height were placed on the plate. Each soil sample was remixed and a sufficient amount was placed in the rubber rings on the plate using a

FIGURE 3. The Extractor and The Ceramic Plate Cell (From Nishio)

spoon. Care was taken to insure that the mixing and preparation process was consistent to minimize the effect of pore sizes and state of packing on the test results (16).

The tubes were next connected and the lid of the extractor closed and tightened with bolts. The end of the outflow tubes were kept constantly under a small amount (± 1") of water in a beaker to insure outflow into a constant environment as far as humidity was concerned and to check against air leaks (16). Pressure was then applied and adjusted to the required value. The pressure was maintained for 24 hours to reach an equilibrium state. At the close of a run the outflow tube was pinched to prevent possible back flow of water when the pressure in the extractor is released. The pressure was released and the lid of the extractor was opened after 24 hours.

The soil samples were transferred to containers and the moisture content of these samples was determined in accordance with ASTM D 2216-63T.

Tests for Method of Preparation Study

To study the effect of methods of preparation of the soil samples on the moisture tension test results, five methods were used. Six soil types were used in this investigation. The soils used were: Nos. 2, 4, 8, 9, 11 and 34 (see Table 2).

Tests were run to determine the moisture content of the soils using each of the five methods of preparation, under 10 psi pressure intensity. Three replications for the entire test were run. The following is a brief description for the methods of preparation used:

Method No. 1

Method 1 was the procedure outlined in U.S.D.A. Handbook No. 60 (23), as suggested by previous work (15):

> "Approximately 30 grams of a representative sample of the soil was placed in a one-half pint fruit jar, and sufficient water was added at one time to bring it nearly to the saturation point. Where a large number of samples was being prepared, as many jars as needed were lined up in a row, and the soil was placed in them. Sufficient water was then added to each sample to bring it nearly to the saturation point. Each sample in turn was then brought to the saturation point, by slowly adding more water and mixing with a spatula.
>
> To determine the end point of saturation, the soil mass was transferred to one side of the jar. If the soil slowly flowed when the jar was tipped to an angle approximately 60 degrees with the horizontal, saturation was assumed. The jars were then capped, and the samples were allowed to stand for an hour or more, after which they were again checked for saturation. The saturated soil was then placed in the rings of the saturated porous plates."

Method No. 2

The second method was that used by Russell and Mickle (16). The samples were mixed with distilled water to the point where the soil mass could be slowly poured out of the jar, with care taken that it was not so

wet as to have free water on the surface when standing. The soil samples were allowed to stand in capped jars for about four hours (minimum) and then placed in the rings on the plate. An excess of water, to an appropriate depth of 1/4 inch, was placed on the plate. The saturated samples were allowed to stand at least 16 hours on the plates, then pressure was applied.

Method No. 3

Method No. 3 was that outlined by Nishio (11):

> "Each soil sample is put into a glass jar filled with distilled water to aid in extracting air from the soil particles, the sample and water were first agitated with a spoon. The soil was left standing for 24 hours with approximately 1" height of excess water. About 50 gm of soil was necessary for one run of test.
>
> After a period of 24 hours the excess water on the surface of the soil in the jar was removed taking care not to disturb the soil sample in the jar. The ceramic plates were wetted with distilled water prior to placing the soil on the plate....After the soil on the plates is placed in the extractor, air pressure was applied....."

Method No. 4

In this method each soil sample of 50 grams weight was put into a jar. Sufficient amounts of distilled water were added and mixed till the point where the soil mass could be slowly poured out of the jar, with care taken that it was not so wet as to have free water on the surface when standing. The samples were allowed to stand

in the capped jars for two hours before placing them on the plates. The ceramic plates were placed in the extractor and wetted with distilled water prior to placing the soil on the plate. Each soil sample was remixed and a sufficient amount was placed in the rings on the plate.

Method No. 5

This was the same procedure as in Method 4, except that no time was allowed for the samples to stand in the jars. That is, each soil sample was placed on the ceramic plate and tested just after the mixing process.

Tests for Atterberg Limits-Moisture Tension Relationships Study

Previous studies indicated that the region between the upper and lower flex points in the moisture tension curves could represent the plasticity index of the soil (16). Furthermore, the interpretation of the two pressure intensities, 3 psi and 20 psi, used by Nishio (11), relative to the moisture tension curves obtained in his study showed that the two values approximately correspond to the two flexes.

To determine the Atterberg limits-moisture tension relationships, four pressure intensities of pressure (6, 10, 12 and 18 psi) were used. These pressure intensities lie in the range (3-20 psi) in which the soil samples exhibit plastic behavior.

For each pressure intensity and using the previously described moisture tension test procedure, the moisture content of each soil was determined. For each of the pressure intensities, four replications were utilized.

Tests for Effect of Time

To study the effect of the time on the moisture tension method results, five soils (Nos. 14, 19, 22, 24 and 34, Table 2) which were expected to require relatively longer equilibrium times were used. Two pressure intensities (10 psi and 18 psi) were used in this test. For each pressure intensity, the moisture content of each of the soil samples was determined after applying the pressure for different periods of time (1, 4, 8, 12, 16 and 24 hours). A new run was made for each time period to insure that the soil samples were always fresh and had not been subjected to any other pressure prior to the test. The tests were run according to the moisture tension test procedure described.

ANALYSIS AND RESULTS

Effect of Method of Preparation on Moisture Tension Results

To study the effect of method of preparation of the soil samples on the moisture tension test results, a randomized complete block design (split-plot design) was used. This design resulted in the following linear model:

$$Y_{ijk} = \mu + R_i + \delta_{(i)} + M_j + RM_{ij} + W_{(ij)} + S_k + RS_{ik} + MS_{jk} + RMS_{ijk} + E_{(ijk)}$$

where

Y_{ijk} = the measured variable, i.e., moisture content at 10 psi pressure intensity

μ = true mean effect for the population

R_i = true effect of the replications of the experiment, $NID(o,\sigma_R^2)$

M_j = true effect of the methods of preparation

S_k = true effect of the soil types

$\delta_{(i)}$ = first restriction error, zero df, $NID(o,\sigma^2_\delta)$

$W_{(ij)}$ = second restriction error, zero df, $NID(o,\sigma^2_W)$

$E_{(ijk)}$ = true random error, zero df, $NID(o,\sigma^2)$

The other terms denote the interactions among the factors R, M, and S. The subscripts assume the values:

$i = 1,2,3$

$j = 1,2,3,4,5$

$k = 1,2,3,4,5,6$

In the ANOVA model, the main effects M and S are fixed while the effect R is random. The linear model was formulated on the basis of the following assumptions: homogeneity of variance, normality, additivity and independence of errors. As there was only one observation for each treatment combination, it was difficult to test the validity of these assumptions. However, analysis of variance is a fairly robust statistical method and is relatively insensitive to violations of the assumptions of normality and homogeneity of variances.

Table 3 summarizes the results of the analysis of variance of the test data. The tests for the significance of main effects and interaction effects were performed at a 5% level of significance ($\alpha = 0.05$). Significant and non-significant effects are denoted by the letter "S" and "NS", respectively.

Before proceeding with an examination of the analysis of variance, it would be in order to explain the linear model used and how the required tests in the analyses were performed.

TABLE 3. Summary of ANOVA – Effect of Method of Preparation on Moisture Tension Test Results

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	EXPECTED MEAN SQUARE	MEAN SQUARES	F-TEST	F-0.5	SIGNIFICANCE
REPLICATIONS (R_i)	2	1.75	$\sigma^2 + 6\sigma_\omega^2 + 30\sigma_\delta^2 + 30\sigma_R^2$	0.88	2.30	3.23	NS
RESTRICTION ERROR $\delta_{(i)}$	0		$\sigma^2 + 6\sigma_\omega^2 + 30\sigma_\delta^2$				
METHOD (M_j)	4	19.89	$\sigma^2 + 6\sigma_\omega^2 + 6\sigma_{RM}^2 + 18\phi_3(M)$	4.97	2.92	3.84	NS
INTERACTION (RM_{ij})	8	13.62	$\sigma^2 + 6\sigma_\omega^2 + 6\sigma_{RM}^2$	1.70			
RESTRICTION ERROR $\omega_{(ij)}$	0		$\sigma^2 + 6\sigma_\omega^2$				
SOIL TYPE (S_K)	5	10029.00	$\sigma^2 + 5\sigma_{RS}^2 + 15\phi_2(S)$	2005.80			
INTERACTION (RS_{iK})	10	4.68	$\sigma^2 + 5\sigma_{RS}^2$	0.47	1.24	2.08	NS
INTERACTION (MS_{jK})	20	15.67	$\sigma^2 + \sigma_{RMS}^2 + 3\phi(MS)$	0.78	2.05	1.84	S
INTERACTION (RMS_{ijK})	40	15.31	$\sigma^2 + \sigma_{RMS}^2$	0.38			
WITHIN ERROR (E_{ijK})	0		σ^2				
TOTAL	89	10099.92					

The nature of this phase of the study resulted in restrictions on randomization at various stages of the experiment, consequently causing "splits" in the design. The first restriction error $\delta_{(i)}$ appears because of the blocking effect due to replications of the experiment. The second restriction error $W_{(ij)}$ results in the model because restrictions on randomization occurred between the methods of preparation of the soil samples. For this reason the tests for main effects and interactions are not straight forward. It is assumed in this model that $\sigma^2_{RMS} = o$, so that the mean square of the interaction (RMS) could be used as an estimate of error mean square.

The tests for significance were performed as indicated by the arrows shown in Table 3. The main effect (methods of preparation) was tested against the (RM) interaction effect. The interactions (RS) and (MS) were tested using the error estimate. To test the significance of the replications R, a conservative test was made utilizing the error estimate. For more detailed information and discussion, the reader is referred to Anderson and McLean (1).

A study of the main effects and interactions indicates the following:

1. There was no significant influence of the effect of methods of preparation of soil samples on the moisture tension method results.

2. The soil type and method of preparation interaction effect (MS), was significant.
3. The effect of replication (R) of the experiment did not have any significant effect on the moisture tension method results.
4. The interaction effect between the replications (R) and the soil types (S) was not significant.

From the previous results it is concluded that:

1. The use of the moisture tension method provides, as expected, a high reproducibility of test results. This is due to the nature of the test equipment and procedure, which minimize the operator variability and experimental error.
2. The method of preparation of the soil samples had no significant effect on the moisture tension test results. This conclusion, however, should be viewed with some caution as the test results apply only to the inference space constituted by the soil test samples and methods of preparation that were used. Since the interaction between the method of preparation and soil type was significant, it is possible that for a certain soil type the methods of preparation may have a significant effect on the moisture tension test results.

Figure 4 shows a plot of the test data resulting from the method of preparation study. Graphs were drawn through the average values obtained from each set of the three repeat measurements. It should be noticed that allowing the saturated samples to stand for longer times before running the test (Method No. 3) gives relatively higher moisture content values.

Since the methods of preparation evaluated in this phase of the study did not have a significant bearing on the moisture tension test results, the choice of a method of preparation of soil samples became primarily a function of convenience and economy of time. Method No. 4 was selected as it best met this criteria. It should be noted that consistency in the method of mixing and preparing the soil samples is of essential value in minimizing changes in the pore sizes and packing state of the soil samples which could affect the moisture tension test results.

Consistency Limits by the Standard Method

The liquid and plastic limits were determined for the thirty-eight soils. A single operator tested four replicates of each soil sample in a completely randomized order. The liquid and plastic limits of the soils along with their mean and standard deviation values are shown in Tables 4 and 5, respectively.

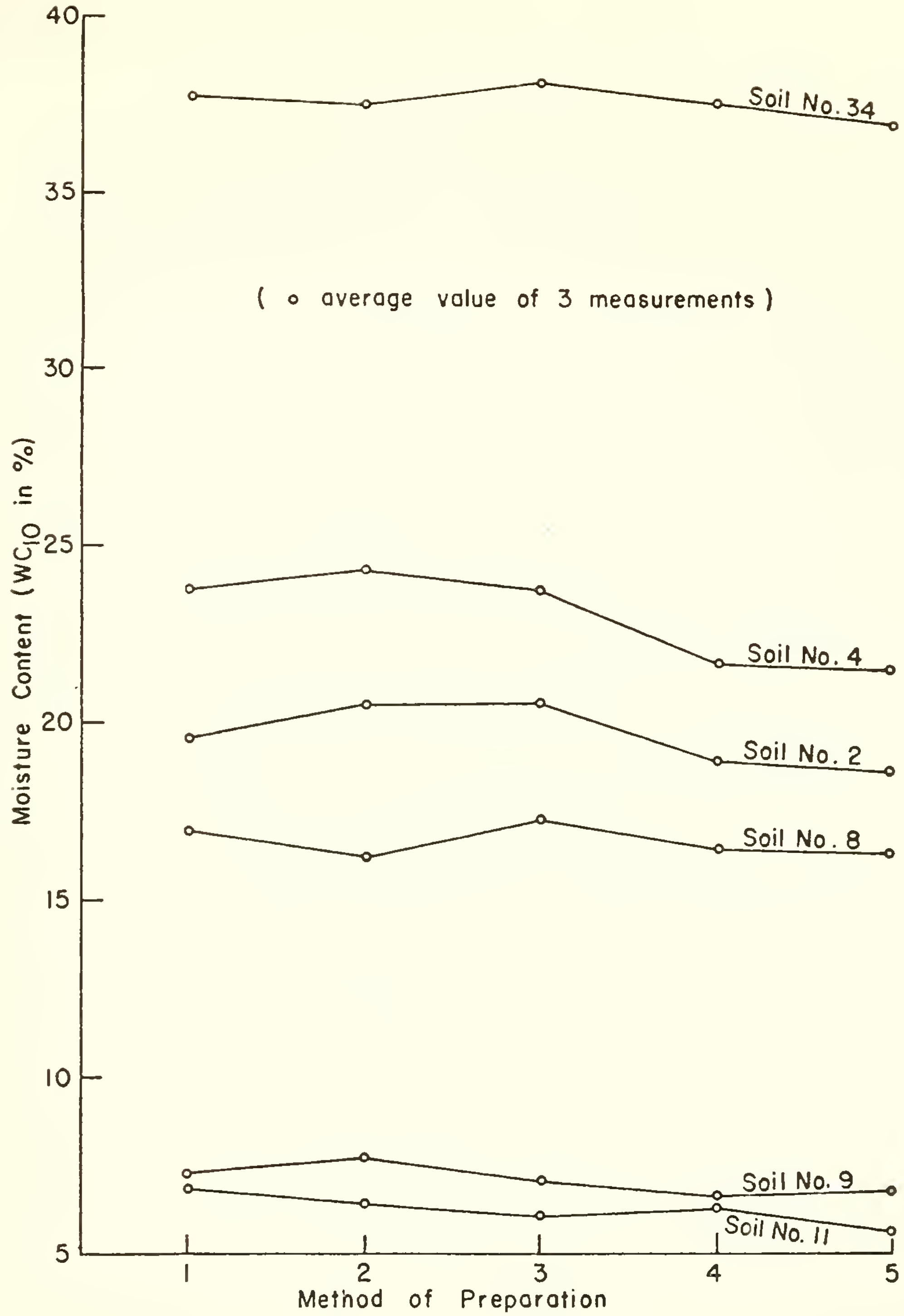

FIGURE 4. Effect of Method of Preparation on The Moisture Tension Test Results

TABLE 4. Summary of Liquid Limit Test Data

SOIL NO.	REPLICATES				MEAN (%)	STANDARD DEVIATION (%)
	1 (%)	2 (%)	3 (%)	4 (%)		
1	25.70	25.60	25.60	25.40	25.58	0.13
2	25.10	25.40	24.80	25.80	25.28	0.43
3	44.80	41.00	43.50	42.30	42.90	1.63
4	30.00	30.00	27.00	28.40	28.85	1.45
5	20.10	18.90	19.00	19.00	19.25	0.57
6	20.30	20.30	19.80	20.10	20.13	0.24
7	22.50	22.60	20.20	21.20	21.63	1.15
8	18.80	18.70	17.90	18.70	18.53	0.42
9	—	—	—	—	N.P.	—
10	19.50	20.80	19.90	19.90	20.03	0.55
11	—	—	—	—	N.P.	—
12	—	—	—	—	N.P.	—
13	—	—	—	—	N.P.	—
14	48.70	50.10	47.40	46.00	48.05	1.76
15	—	—	—	(18.10)*	18.10	—
16	—	—	—	—	N.P.	—
17	41.00	39.70	41.30	40.20	40.55	0.73
18	41.00	39.90	39.30	38.30	39.63	1.13
19	36.10	36.20	34.30	35.90	35.63	0.89
20	33.40	33.40	32.90	33.50	33.30	0.27
21	27.20	26.20	26.30	25.30	26.25	0.78
22	27.60	27.00	28.00	27.70	27.58	0.42
23	31.70	30.00	29.80	30.80	30.58	0.87
24	28.40	28.40	27.40	28.60	28.20	0.54
25	29.60	27.50	29.00	29.10	28.80	0.91

TABLE 4, Cont.

SOIL NO.	REPLICATES 1 (%)	2 (%)	3 (%)	4 (%)	MEAN (%)	STANDARD DEVIATION (%)
26	27.20	27.00	26.50	25.90	26.65	0.58
27	22.90	22.70	22.40	22.00	22.50	0.39
28	21.50	21.30	20.60	21.10	21.13	0.39
29	24.30	24.70	24.00	23.80	24.20	0.39
30	18.70	19.00	19.20	18.70	18.90	0.25
31	20.80	19.90	20.10	20.30	20.28	0.39
32	18.90	19.00	18.50	19.20	18.90	0.29
33	47.90	45.50	46.00	46.20	46.40	1.04
34	49.80	49.90	48.50	49.40	49.40	0.64
35	—	—	—	(19.00)	19.00	—
36	—	—	—	—	N.P.	—
37	—	—	—	(18.00)	18.00	—
38	—	—	—	—	N.P.	—
					AVERAGE STANDARD DEVIATION	0.69

* Values in Parentheses Were Obtained From One Test Only

TABLE 5. Summary of Plastic Limit Test Data

SOIL NO.	REPLICATES				MEAN	STANDARD DEVIATION
	1 (%)	2 (%)	3 (%)	4 (%)	(%)	(%)
1	15.30	15.40	15.10	15.80	15.40	0.29
2	15.40	16.20	16.00	15.40	15.75	0.41
3	26.80	26.90	26.70	25.60	26.50	0.61
4	25.30	24.50	24.80	25.60	25.05	0.49
5	14.70	14.30	14.60	14.60	14.55	0.17
6	13.60	14.00	14.10	14.30	14.00	0.29
7	16.80	16.20	15.80	15.80	16.15	0.47
8	13.10	14.10	13.50	13.80	13.63	0.43
9	—	—	—	—	N.P.	—
10	16.00	16.60	16.60	16.20	16.35	0.30
11	—	—	—	—	N.P.	—
12	—	—	—	—	N.P.	—
13	—	—	—	—	N.P.	—
14	26.80	27.30	26.90	26.80	26.95	0.24
15	—	—	—	(15.60)*	15.60	—
16	—	—	—	—	N.P.	—
17	22.50	22.60	22.60	23.50	22.80	0.47
18	21.10	21.90	21.70	22.40	21.78	0.54
19	24.60	24.40	24.20	25.10	24.58	0.39
20	19.40	20.80	18.60	19.20	19.50	0.94
21	16.00	16.20	16.50	16.20	16.22	0.21
22	19.10	18.60	19.10	19.70	19.13	0.45
23	18.10	17.80	17.40	17.70	17.75	0.29
24	17.00	17.50	16.50	17.10	17.03	0.41
25	16.90	16.60	16.70	16.90	16.78	0.15

TABLE 5, Cont.

SOIL NO.	REPLICATES 1 (%)	2 (%)	3 (%)	4 (%)	MEAN (%)	STANDARD DEVIATION (%)
26	19.00	19.00	19.00	19.20	19.05	0.10
27	15.90	15.20	15.70	15.60	15.60	0.29
28	14.10	14.30	13.80	14.10	14.08	0.21
29	16.70	17.20	18.10	16.90	17.23	0.62
30	13.80	13.70	13.90	14.10	13.88	0.17
31	14.50	14.60	14.50	14.90	14.63	0.19
32	13.70	13.80	13.80	14.10	13.85	0.17
33	29.30	29.20	30.70	30.80	30.00	0.87
34	30.50	30.10	29.50	30.70	30.20	0.53
35	—	—	—	(16.50)	16.50	—
36	—	—	—	—	N.P.	—
37	—	—	—	(16.00)	16.00	—
38	—	—	—	—	N.P.	—
					AVERAGE STANDARD DEVIATION	0.38

* Values in Parentheses Were Obtained From One Test Only

The mean liquid limit values ranged between 18.53% and 49.40% moisture content. The average standard deviation of replicates from the mean was approximately 0.69 percent moisture content, the largest standard deviation was 1.76 percent moisture content. The plastic limit values ranged between 13.63% and 30.20% moisture content. The average standard deviation of the replicates from the mean was approximately 0.38 percent moisture content, the largest standard deviation was 0.87 percent moisture content.

To study the reproducibility of the standard liquid and plastic limit results, the analysis of variance was based upon a completely randomized design using the model:

$$Y_{ij} = \mu + S_j + E_{(ij)}$$

where

Y_{ij} = measured variable

μ = true mean effect of the population

S_j = true effect of the soil type

$E_{(ij)}$ = random error, $NID(0,\sigma^2)$

The subscripts assume the values:

$i = 1,3,3,4$

$j = 1,2,.....28$

In the ANOVA model, the mean effect S is fixed.

Table 6, summarizes the results of the analysis of variance of both liquid limit and plastic limit test data. It is concluded that the error variations of the liquid limit (the variation between tests of a given soil) is larger than that of the plastic limit test results. In other words, the plastic limit test results are relatively more reproducible than the liquid limit test results. In addition, it should be recalled that since there is no replication effect for the moisture tension method (refer to Table 3, page 33 and Table 16, page 72) it is indicated that the learning effect by the operator is minimal. Hence, it is suggested the method has an inherent advantage over the standard test function's point of view.

Prediction of Liquid and Plastic Limit of Soils by the Moisture Tension Method

In this phase of the study, the equilibrium moisture content of the soil samples was determined utilizing four pressure intensities. The pressure intensities used in

TABLE 6. Summary of ANOVA of The Liquid Limit and Plastic Limits

CASE	SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE
LIQUID LIMIT (LL)	SOIL S_j	27	9812.99	363.44
	ERROR $E_{(ij)}$	84	54.27	0.65
	TOTAL	111	9867.26	
PLASTIC LIMIT (PL)	SOIL TYPE S_j	27	2787.54	103.24
	ERROR $E_{(ij)}$	84	15.69	0.19
	TOTAL	111	2803.23	

F TEST (LL vs PL) $F = \frac{0.65}{0.19} = 3.42^{*}$

* SIGNIFICANT AT $\alpha = .05$ LEVEL

the moisture tension method were: 6, 10, 12 and 18 psi. For each pressure intensity four replicate tests were run.

Linear regression models were hypothesized to study the relationships between the measured variables, liquid limit and plastic limit and independent variable, WC_i (the symbol WC_i will be used to represent the moisture content obtained under i psi pressure intensity). A separate model was evaluated for each of the four pressure intensities. Non-plastic soils were excluded from the study.

The data for the regression analysis were handled in two different ways. The first was designated as "random combination" and the other as "average values".

Random Combination

In the random combination scheme, the four liquid limit values for each soil were randomly combined with the corresponding four moisture content values obtained at a given pressure intensity to form a set of four readings. The process was repeated for the plastic limit data.

The data obtained for the 28 soil samples were tested for homogeneity of variance. The results of Foster-Burr test are shown in Table 7.

Table 7. Foster-Burr Test for Homogeneity of Variance

Variable	Degree of Freedom	No. of Samples	$Q_{Statistic}$	$Q_{Critical}$
LL	3	28	0.0877	0.092**
PL	3	28	0.0776	0.082*

* $\alpha = 0.01$ ** $\alpha = 0.001$

In the case of the plastic limit data, the test showed no significant difference in the variance at the 1% level of significance. The homogeneity of variance test for the liquid limit data was not significant at 0.1% level of significance. The assumption of the homogeneity of variance was accepted and there was no need of transforming the dependent variables.

Average Values

In the "average values" scheme, the mean value of the four replicates of the liquid and plastic limit tests for each soil was used as the dependent variable. Similarly, the mean WC_i value for each soil was used as the independent variable.

In case of 6, 10 and 12 psi pressure intensities, 28 cases were available for the regression analysis, this number being the same as that of the number of soil types. In case of 18 psi pressure intensity, only 27 cases were

available, as the amount of the soil No. 1 was not enough to run the moisture tension test.

Interpretation of the Regression Analysis Results

The models obtained from the regression analysis of the test data were examined and the ones providing the best fit of the data were selected. The criterion used to evaluate the best regression equation is based on the coefficient of determination, R^2. The coefficient of determination is the ratio of the variation explained by the regression equation to the total variation of the data about the mean. Also, the significance of the regression was tested by an appropriate F-test at an α level of 0.05. The residuals obtained from the regression analysis was examined to determine if they were correlated. It was observed that the residuals did not show any predominant trend.

The results of the regression analysis are summarized in Tables 8 through 11.

An examination of these results indicates that linear first-order regression models are the most appropriate for representing the relationship between consistency limits (LL and PL) and the moisture content WC_i. The data point out that:

TABLE 8. Prediction Equations For The Liquid and Plastic Limits (P = 6 psi)

CASE	SCHEME	MODEL	R^2	STAND. ERROR	N	F
LL	RANDOM COMBINATION	$\widehat{LL} = -3.5863 + 1.3201\ WC_6$	0.93	2.58	112	1363.88
	AVERAGE VALUES	$\widehat{LL} = -3.7939 + 1.3279\ WC_6$	0.94	2.36	28	414.53
PL	RANDOM COMBINATION	$\widehat{PL} = 1.4094 + 0.7097\ WC_6$	0.94	1.22	112	1764.81
	AVERAGE VALUES	$\widehat{PL} = 1.3445 + 0.7120\ WC_6$	0.95	1.13	28	520.36

All F-Values are Significant at $\alpha = 0.05$

N = Number of Samples

R^2 = Coefficient of Determination

TABLE 9. Prediction Equations For The Liquid and Plastic Limits (P = 10 psi)

CASE	SCHEME	MODEL	R^2	STAND. ERROR	N	F
LL	RANDOM COMBINATION	$\widehat{LL} = -3.5437 + 1.4867\ WC_{10}$	0.95	2.18	112	976.68
	AVERAGE VALUES	$\widehat{LL} = -3.6626 + 1.4922\ WC_{10}$	0.95	2.12	28	516.54
PL	RANDOM COMBINATION	$\widehat{PL} = 1.9906 + 0.7737\ WC_{10}$	0.90	1.59	112	988.07
	AVERAGE VALUES	$\widehat{PL} = 1.9257 + 0.7767\ WC_{10}$	0.91	1.59	28	256.26

All F-Values are Significant at $\alpha = 0.05$

N = Number of Samples

R^2 = Coefficient of Determination

TABLE 10. Prediction Equations For The Liquid and Plastic Limits (P = 12 psi)

CASE	SCHEME	MODEL	R^2	STAND. ERROR	N	F
LL	RANDOM COMBINATION	$\widehat{LL} = -2.7809 + 1.4892\ WC_{12}$	0.95	2.09	112	2151.29
	AVERAGE VALUES	$\widehat{LL} = -2.8652 + 1.4953\ WC_{12}$	0.96	1.97	28	603.42
PL	RANDOM COMBINATION	$\widehat{PL} = 2.7699 + 0.7570\ WC_{12}$	0.87	1.85	112	706.06
	AVERAGE VALUES	$\widehat{PL} = 2.6970 + 0.7605\ WC_{12}$	0.88	1.83	28	182.66

All F-Values are Significant at $\alpha = 0.05$

N = Number of Samples

R^2 = Coefficient of Determination

TABLE 11. Prediction Equations For The Liquid and Plastic Limits (P = 18 psi)

CASE	SCHEME	MODEL	R^2	STAND. ERROR	N	F
LL	RANDOM COMBINATION	$\widehat{LL} = -1.9158 + 1.5029\ WC_{18}$	0.92	2.68	108	1262.76
	AVERAGE VALUES	$\widehat{LL} = -2.0446 + 1.5091\ WC_{18}$	0.93	2.62	27	330.18
PL	RANDOM COMBINATION	$\widehat{PL} = 3.9766 + 0.7299\ WC_{18}$	0.78	2.41	108	367.69
	AVERAGE VALUES	$\widehat{PL} = 3.9114 + 0.7331\ WC_{18}$	0.78	2.44	27	90.06

All F-Values are Significant at $\alpha = 0.05$

N = Number of Samples

R^2 = Coefficient of Determination

1. The prediction models obtained for both the liquid and plastic limits show a high coefficient of determination, R^2. Also, a linear relationship exists between the liquid or plastic limit and the equilibrium moisture content for each of the pressure intensities utilized in this investigation (6, 10, 12 and 18 psi).
2. The regression models obtained for the prediction of the liquid limit show a higher R^2 value than that obtained for the prediction of the plastic limit values.
3. For the liquid limit prediction models, the R^2 values remain almost the same (0.92-0.96) with changes in the pressure intensity. Contrarily, for the plastic limit prediction models, the R^2 values decrease directly with the increase in pressure intensity utilized. The prediction model obtained at 6 psi has an R^2 value of about 0.95, and that at 18 psi has a $R^2 = 0.78$.
4. Using the average values in the regression analysis eliminates a part of the variation among the replicate measurements, which may make the coefficient of determination R^2 misleadingly high. However, this study indicates that there is very little difference in R^2 due to the use of the two schemes (random combination vs. average

values). The use of the prediction models obtained by utilizing the random combination scheme could better represent the inference space for this study.

Prediction Using a Single Pressure

Figures 5 through 12 show the relationship between the liquid and plastic limit and the moisture content, WC_i for the various pressure intensities. All test data points were plotted with the prediction equation obtained using the random combination scheme. On the basis of these test data, it was decided to study the accuracy of using a single pressure; 10 psi pressure was selected for study. This value was selected since a high R^2 value was obtained for both the liquid and plastic limit prediction models for this pressure. Though the models indicate that utilizing a pressure intensity of 6 psi would result in even a higher coefficient of determination R^2, using such a relatively low pressure intensity requires more experimental control and careful adjustments of the pressure regulators. The equilibrium moisture content is a function of the pressure intensity applied. For low pressure WC_i is higher than that obtained under high pressures. Consequently it was observed that transferring the soil samples from the ceramic plates to

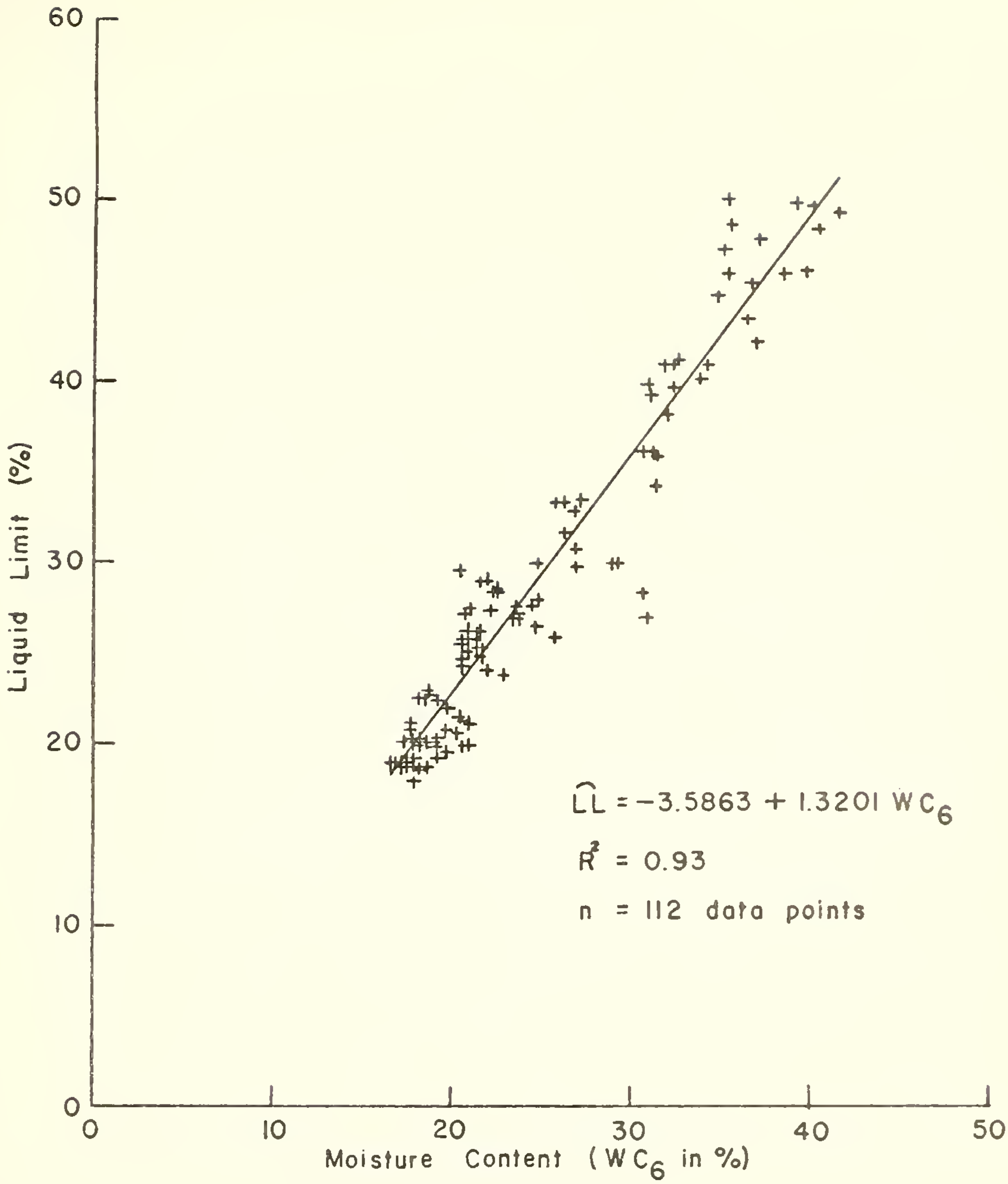

FIGURE 5. Relationship Between The Liquid Limit and Moisture Content at 6 psi

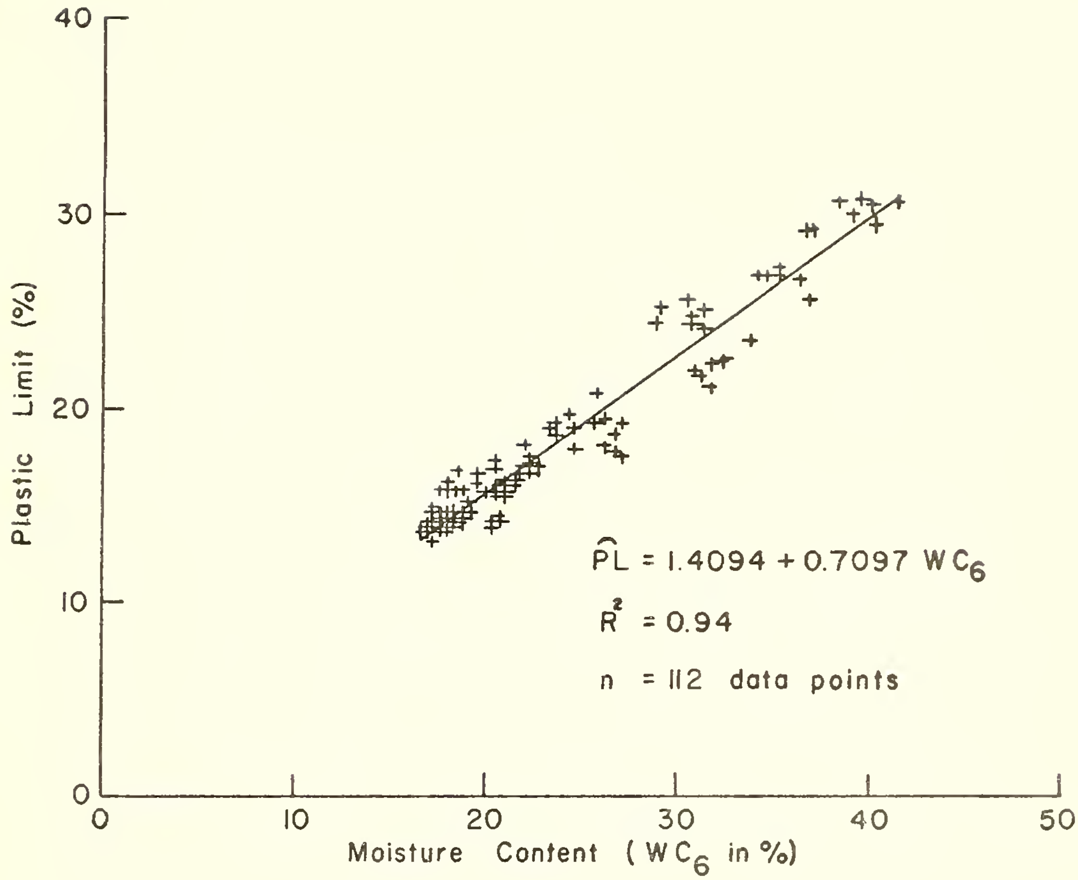

FIGURE 6 . Relationship Between The Plastic Limit and Moisture Content at 6psi

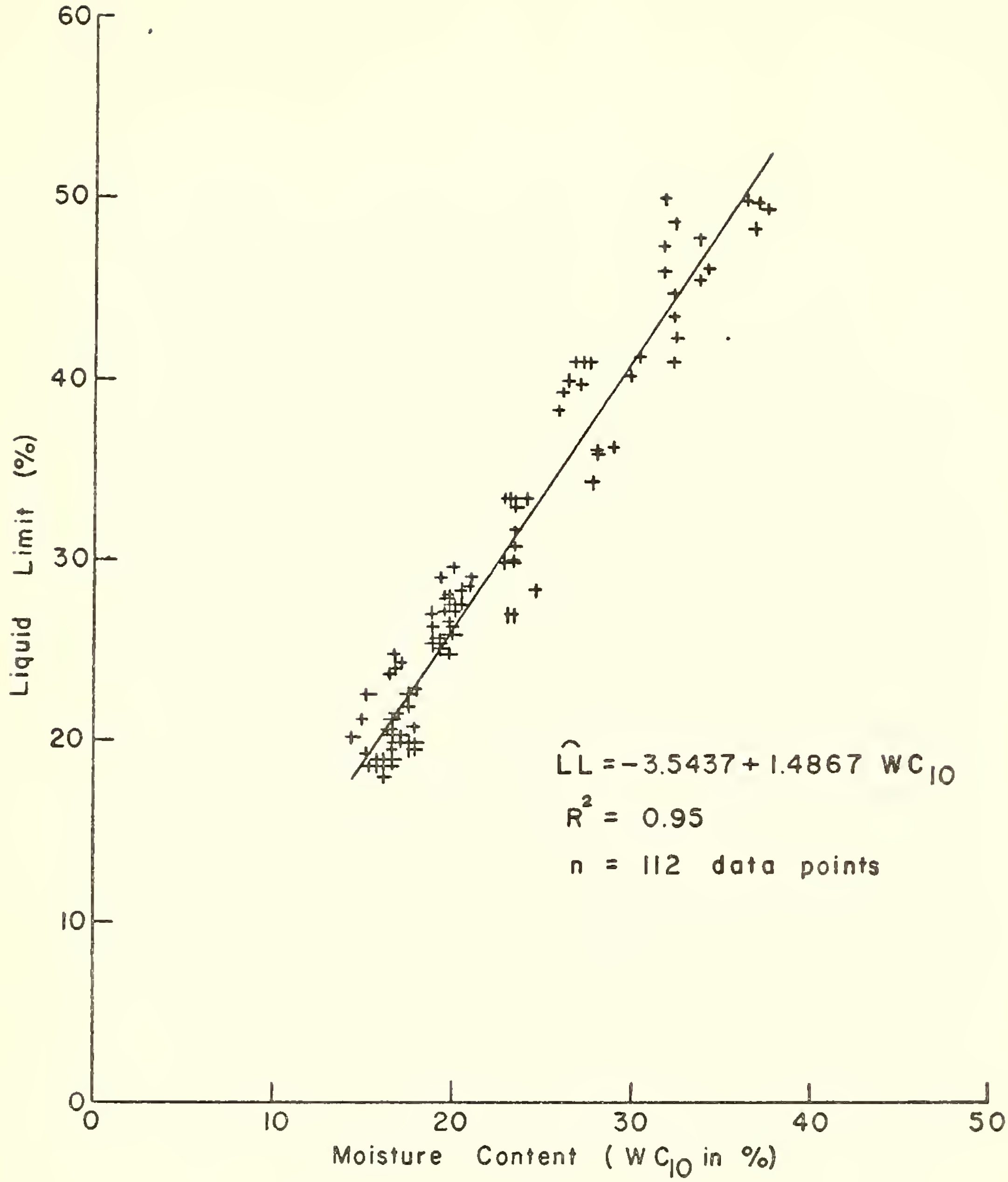

FIGURE 7. Relationship Between The Liquid Limit and Moisture Content at 10psi

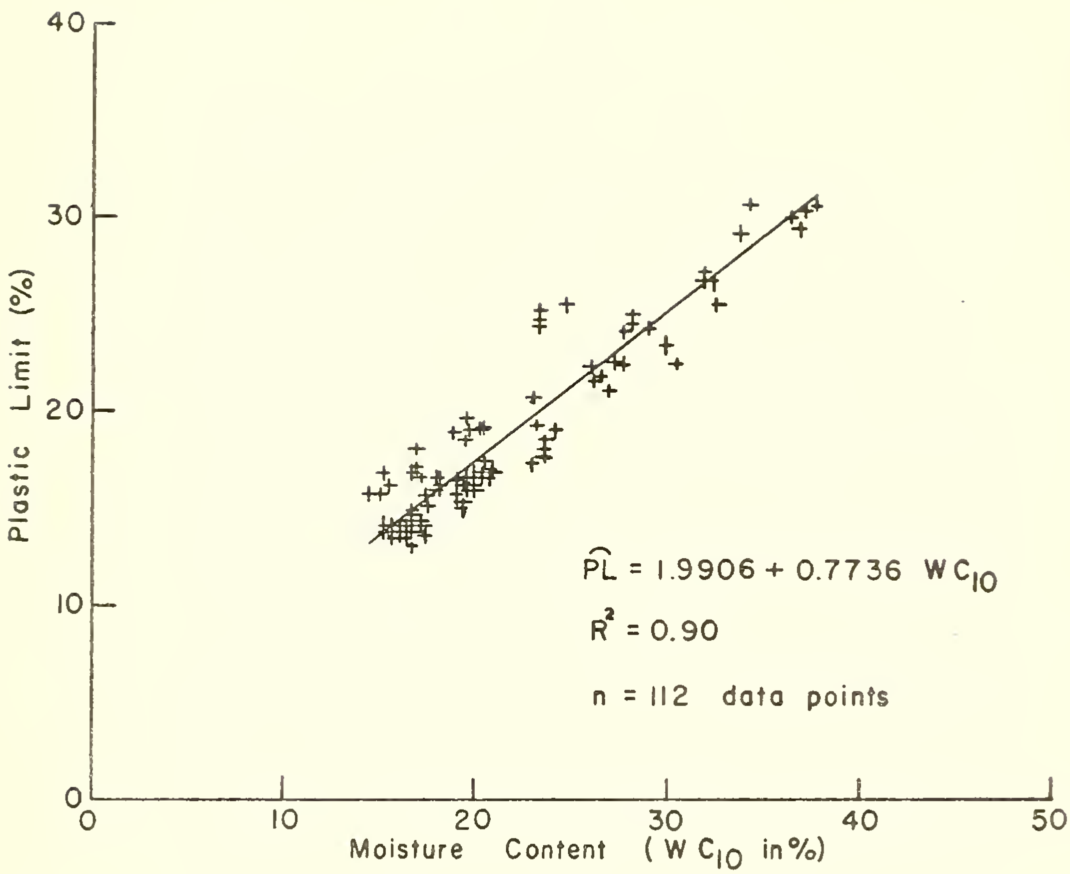

FIGURE 8. Relationship Between The Plastic Limit and Moisture Content at 10psi

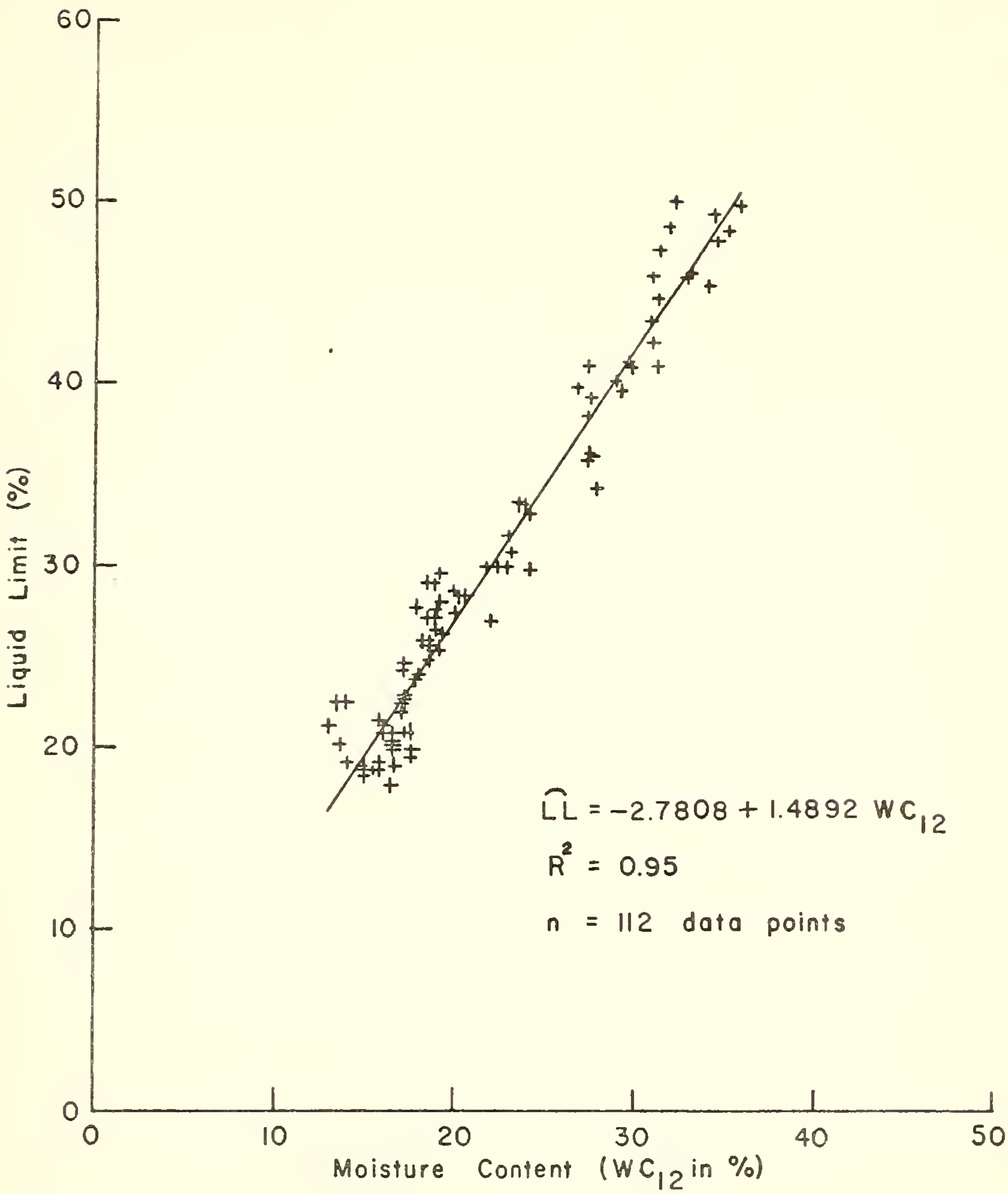

FIGURE 9. Relationship Between The Liquid Limit and Moisture Content at 12 psi

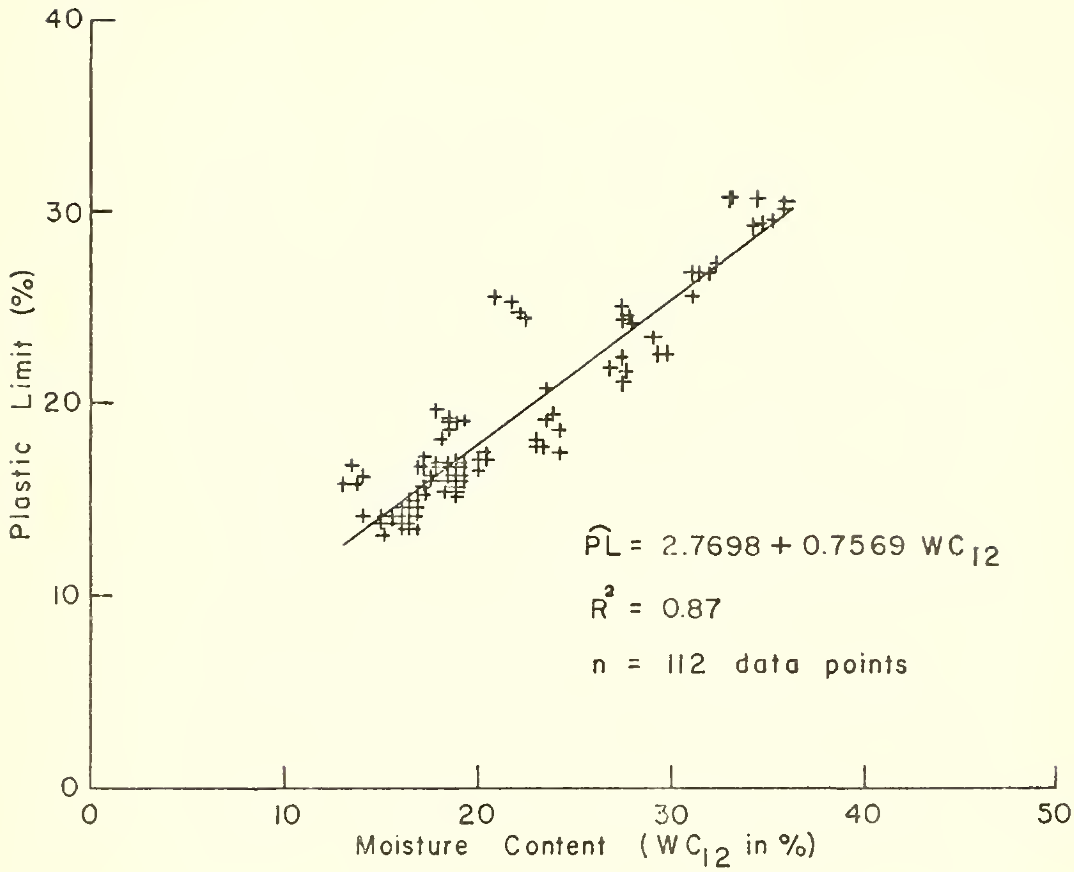

FIGURE 10. Relationship Between The Plastic Limit and Moisture Content at 12 psi

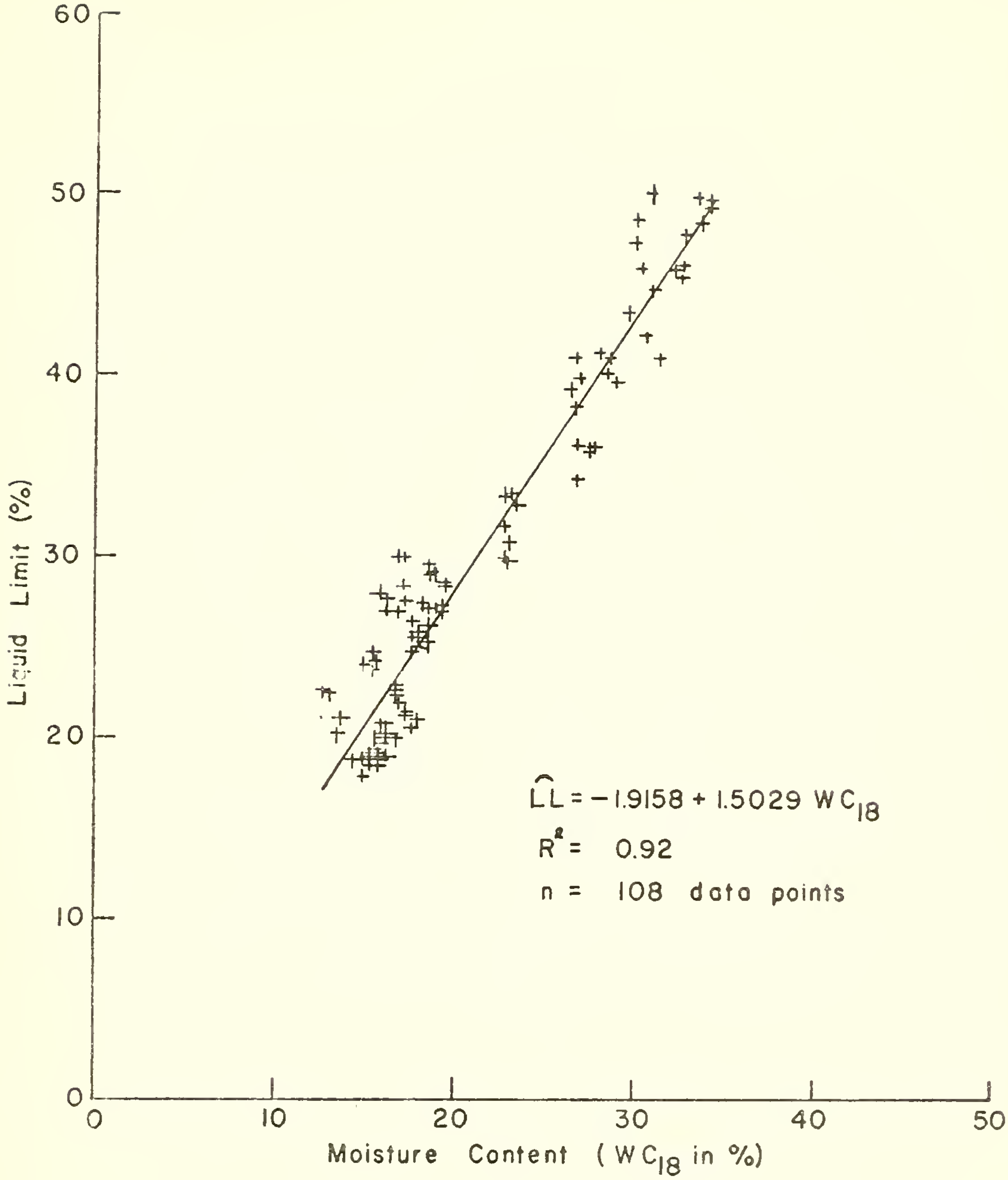

FIGURE 11. Relationship Between The Liquid Limit and Moisture Content at 18psi

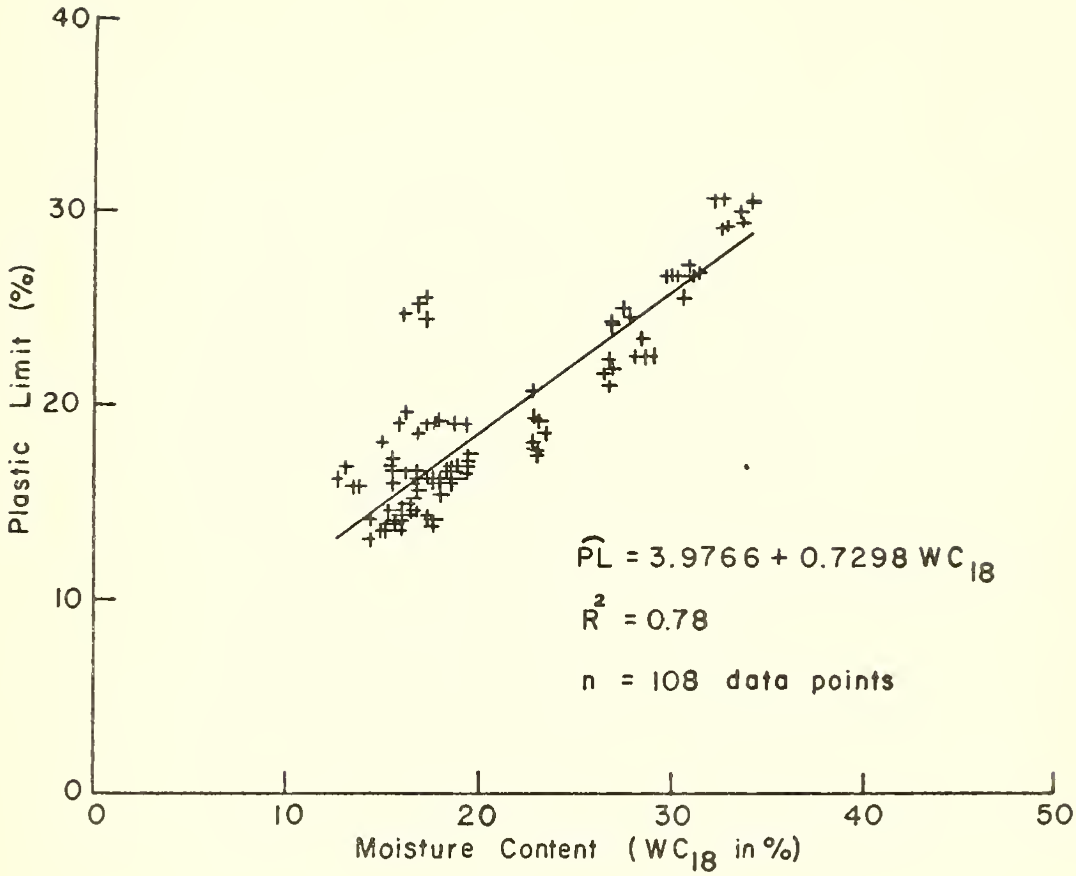

FIGURE 12. Relationship Between The Plastic Limit and Moisture Content at 18 psi

the containers after releasing the pressure was easier at 10 psi pressure intensity.

Tables 12 and 13 present a comparison between the LL and PL values as obtained by the standard ASTM method and their predicted values as obtained using the moisture tension method results at 10 psi pressure intensity. The deviation between the standard LL and PL test results and the predicted values range from 1 to 2 percent moisture content. Only in some cases, e.g. soil No. 4, the deviation in the PL results reaches 5% moisture content and soils No. 14 and 18 show a deviation of about 6% moisture content in the LL results. It appears that the deviations of the predicted LL and PL values from the observed values are compatible with those obtained in replicated standard LL and PL test results.

Simplifying the Regression Models

To make the prediction models less cumbersome and easy to handle, it was decided to simplify the regression coefficients. As the liquid and plastic limit values are generally determined to the nearest whole percent moisture content; rounding off the regression coefficients in the prediction equations will not affect the results appreciably. In Tables 12 and 13, the predicted liquid and plastic limit values obtained by using the following prediction equations:

TABLE 12. Liquid Limit Values Obtained From The Moisture Tension Method Compared With The Standard Liquid Limit Test Results

SOIL NO	LL^{o}	WC_{10}^{b}	$\widehat{LL}^{c}$	DEV^{d}	$\widehat{LL}^{e}$	DEV
1	25.70	19.25	25.08	0.62	25.38	0.32
	25.60	19.28	25.12	0.48	25.42	0.18
	25.60	19.23	25.05	0.55	25.34	0.26
	25.40	19.05	24.78	0.62	25.08	0.32
2	25.10	19.49	25.43	-0.33	25.74	0.64
	25.40	19.31	25.17	0.23	25.46	-0.06
	24.80	19.82	25.92	-1.12	26.23	-1.43
	25.80	19.52	25.48	0.32	25.78	0.02
3	44.80	32.29	44.46	0.34	44.94	0.14
	41.00	32.36	44.57	-3.57	45.04	-4.04
	43.50	32.33	44.52	-1.02	45.00	-1.50
	42.30	32.57	44.88	-2.58	45.36	-3.06
4	30.00	23.34	31.16	-1.16	31.51	-1.51
	30.00	23.26	31.04	-1.04	31.39	-1.39
	27.00	23.28	31.07	-4.07	31.42	-4.42
	28.40	24.66	33.12	-4.72	33.49	-5.09
5	20.10	16.90	21.58	-1.48	21.85	-1.75
	18.90	17.01	21.75	-2.85	22.02	-3.12
	19.00	16.80	21.43	-2.43	21.70	-2.70
	19.00	16.98	21.70	-2.70	21.97	-2.97
6	20.30	17.36	22.27	-1.97	22.54	-2.24
	20.30	17.27	22.13	-1.83	22.40	-2.10
	19.80	17.55	22.55	-2.75	22.82	-3.02
	20.10	17.22	22.06	-1.96	22.33	-2.23
7	22.50	15.22	19.08	3.42	19.33	3.17
	22.60	15.50	19.50	3.10	19.75	2.85
	20.20	14.43	17.91	2.29	18.14	2.06
	21.20	14.98	18.73	2.47	18.97	2.23
8	18.80	16.64	21.20	-2.40	21.46	-2.66
	18.70	16.60	21.14	-2.44	21.40	-2.70
	17.90	16.35	20.76	-2.86	21.02	-3.12
	18.70	16.50	20.99	-2.29	21.25	-2.55
10	19.50	17.92	23.10	-3.60	23.38	-3.88
	20.80	17.95	23.14	-2.34	23.42	-2.62
	19.90	18.08	23.34	-3.44	23.62	-3.72
	19.90	18.19	23.50	-3.60	23.78	-3.88
14	48.70	32.37	44.58	4.12	45.06	3.64
	50.10	31.88	43.85	6.25	44.32	5.78
	47.40	31.77	43.69	3.71	44.16	3.24
	46.00	31.81	43.75	2.25	44.22	1.78
17	41.00	27.72	37.67	3.33	38.08	2.92
	39.70	27.23	36.94	2.76	37.34	2.36
	41.30	30.38	41.62	-0.32	42.07	-0.77
	40.20	29.93	40.95	-0.75	41.40	-1.20
18	41.00	26.93	36.49	4.51	36.90	4.10
	39.90	26.49	35.84	4.06	36.24	3.66
	39.30	26.13	35.30	4.00	35.70	3.60
	38.30	25.97	35.07	3.23	35.46	2.84
19	36.10	28.10	38.23	-2.13	38.65	-2.55
	36.20	29.02	39.60	-3.40	40.03	-3.83
	34.30	27.74	37.70	-3.40	38.11	-3.81
	35.90	28.13	38.28	-2.38	38.70	-2.80
20	33.40	23.21	30.96	2.44	31.32	2.08
	33.40	22.97	30.61	2.79	30.96	2.44
	32.90	23.66	31.63	1.27	31.99	0.91
	33.50	24.16	32.38	1.12	32.74	0.76
21	27.20	20.02	26.22	0.98	26.53	0.67
	26.20	19.92	26.07	0.13	26.38	-0.18
	26.30	19.02	24.73	1.57	25.03	1.27
	25.30	19.33	25.20	0.10	25.50	-0.20
22	27.60	20.20	26.49	1.11	26.80	0.80
	27.00	19.44	25.36	1.64	25.66	1.34
	28.00	19.80	25.89	2.11	26.20	1.80
	27.70	19.54	25.51	2.19	25.81	1.89
23	31.70	23.57	31.50	0.20	31.86	-0.16
	30.00	23.47	31.35	-1.35	31.70	-1.70
	29.80	22.96	30.59	-0.79	30.94	-1.14
	30.80	23.55	31.47	-0.67	31.82	-1.02
24	28.40	20.62	27.11	1.29	27.16	1.24
	28.40	20.44	26.85	1.55	27.43	0.97
	27.40	20.69	27.22	0.18	27.54	-0.14
	28.60	20.91	27.54	1.06	27.86	0.74
25	29.60	20.10	26.34	3.26	26.65	2.95
	27.50	20.02	26.22	1.28	26.53	0.97
	29.00	19.37	25.25	3.75	25.56	3.44
	29.10	21.14	27.89	1.21	28.21	0.89
26	27.20	19.54	25.51	1.69	25.81	1.39
	27.00	18.84	24.47	2.53	24.76	2.24
	26.50	19.70	25.75	0.75	26.05	0.45
	25.90	20.35	26.71	-0.81	27.02	-1.12
27	22.90	17.94	23.13	-0.23	23.41	-0.51
	22.70	17.56	22.56	-0.14	22.84	-0.14
	22.40	17.49	22.46	-0.06	22.74	-0.34
	22.00	17.58	22.59	-0.59	22.87	-0.87
28	21.50	16.91	21.60	-0.10	21.86	-0.36
	21.30	16.47	20.94	0.36	21.20	0.10
	20.60	16.44	20.90	-0.30	21.16	-0.56
	21.10	16.51	21.00	0.10	21.26	0.16
29	24.30	17.11	21.89	2.41	22.16	2.14
	24.70	16.83	21.48	3.22	21.74	2.96
	24.00	16.92	21.61	2.39	21.88	2.12
	23.80	16.62	21.17	2.63	21.43	2.37
30	18.70	16.14	20.45	-1.75	20.71	-2.01
	19.00	15.92	20.13	-1.13	20.38	-1.38
	19.20	15.58	19.62	-0.42	19.87	-0.67
	18.70	15.71	19.81	-1.11	20.06	-1.36
31	20.80	16.75	21.36	-0.56	21.62	-0.82
	19.90	16.60	21.14	-1.24	21.40	-1.50
	20.10	16.82	21.46	-1.36	21.73	-1.63
	20.30	16.75	21.36	-1.06	21.62	-1.32
32	18.90	15.81	19.96	-1.06	20.22	-1.32
	19.00	15.58	19.62	-0.62	19.87	-0.87
	18.50	15.38	19.32	-0.82	19.57	-1.07
	19.20	15.22	19.08	0.12	19.33	-0.13
33	47.90	33.80	46.71	1.19	47.20	0.70
	45.50	33.79	46.69	-1.19	47.18	-1.68
	46.00	34.37	47.56	-1.56	48.06	-2.06
	46.20	34.26	47.39	-1.19	47.89	-1.69
34	49.80	37.10	51.61	-1.81	52.15	-2.35
	49.90	36.45	50.65	-0.75	51.18	-1.28
	48.40	36.86	51.26	-2.86	51.79	-3.39
	49.40	37.70	52.51	-3.11	53.05	-3.65

o Standard ASTM Method Results

b Moisture Content at 10psi Pressure Intensity

c Liquid Limit as Predicted From The Equation

$$\widehat{LL} = -3.5437 + 1.4867\, WC_{10}$$

d Deviation, Standard Minus Predicted Values

e Liquid Limit as Predicted From The Equation

$$\widehat{LL} = -3.5 + 1.5\, WC_{10}$$

TABLE 13. Plastic Limit Values Obtained From The Moisture Tension Method Compared With The Standard Plastic Limit Test Results

SOIL NO	PL^{a}	WC_{10}^{b}	$\widehat{PL}^{c}$	DEV^{d}	$\widehat{PL}^{e}$	DEV
1	15.30	19.25	16.88	−1.58	16.44	−1.14
	15.40	19.28	16.91	−1.51	16.46	−1.06
	15.10	19.23	16.87	−1.77	16.42	−1.32
	15.80	19.05	16.73	−0.93	16.29	−0.49
2	15.40	19.49	17.07	−1.67	16.62	−1.22
	16.20	19.31	16.93	−0.73	16.48	−0.28
	16.00	19.82	17.32	−1.32	16.86	−0.86
	15.40	19.52	17.09	−1.69	16.64	−1.24
3	26.80	32.29	26.97	−0.17	26.22	−0.58
	26.90	32.36	27.03	−0.13	26.27	−0.63
	26.70	32.33	27.00	−0.30	26.25	0.45
	25.60	32.57	27.19	−1.59	26.43	−0.83
4	25.30	23.34	20.05	5.25	19.50	5.80
	24.50	23.26	19.99	4.51	19.44	5.06
	24.80	23.28	20.00	4.80	19.46	5.34
	25.60	24.66	21.07	4.53	20.50	5.10
5	14.70	16.90	15.07	−0.37	14.68	0.02
	14.30	17.01	15.15	−0.85	14.76	−0.46
	14.60	16.80	14.99	−0.39	14.60	−0.00
	14.60	16.98	15.13	−0.53	14.74	−0.14
6	13.60	17.36	15.42	−1.82	15.02	−1.42
	14.00	17.27	15.35	−1.35	14.95	−0.95
	14.10	17.55	15.57	−1.47	15.16	−1.06
	14.30	17.22	15.31	−1.01	14.92	−0.62
7	16.80	15.22	13.77	3.03	13.42	3.38
	16.20	15.50	13.98	2.22	13.62	2.58
	15.80	14.43	13.15	2.65	12.82	2.98
	15.80	14.98	13.58	2.22	13.24	2.56
8	13.10	16.64	14.86	−1.76	14.48	−1.38
	14.60	16.60	14.83	−0.23	14.45	0.15
	13.50	16.35	14.64	−1.14	14.26	−0.76
	13.80	16.50	14.76	−0.96	14.38	−0.58
10	16.00	17.92	15.85	0.15	15.44	0.56
	16.60	17.95	15.88	0.72	15.46	1.14
	16.60	18.08	15.98	0.62	15.56	1.04
	16.20	18.19	16.06	0.14	15.64	0.56
14	26.80	32.37	27.03	−0.23	26.28	0.52
	27.30	31.88	26.66	0.64	25.91	1.39
	26.90	31.77	26.57	0.33	25.83	1.07
	26.80	31.81	26.60	0.20	25.86	0.94
17	22.50	27.72	23.44	−0.94	22.79	−0.29
	22.60	27.23	23.06	−0.46	22.42	0.18
	22.60	30.38	25.49	−2.89	24.78	−2.18
	23.50	29.93	25.15	−1.65	24.45	−0.95
18	21.10	26.93	22.83	−1.73	22.20	−1.10
	21.90	26.49	22.49	−0.59	21.87	0.03
	21.70	26.13	22.21	−0.51	21.60	0.10
	22.40	25.97	22.08	0.32	21.48	0.92
19	24.60	28.10	23.73	0.87	23.08	1.52
	24.40	29.02	24.44	−0.04	23.76	0.64
	24.20	27.74	23.45	0.75	22.80	1.40
	25.10	28.13	23.75	1.35	23.10	2.00
20	19.40	23.21	19.95	−0.55	19.41	−0.01
	20.80	22.97	19.76	1.04	19.23	1.57
	18.60	23.68	20.30	−1.70	19.74	−1.14
	19.20	24.16	20.68	−1.48	20.12	−0.92
21	16.00	20.02	17.48	−1.48	17.02	−1.02
	16.20	19.92	17.40	−1.20	16.94	−0.74
	16.50	19.02	16.71	−0.21	16.26	0.24
	16.20	19.33	16.95	−0.75	16.50	−0.30
22	19.10	20.20	17.62	1.48	17.15	1.95
	18.60	19.44	17.03	1.57	16.58	2.02
	19.10	19.80	17.31	1.79	16.85	2.25
	19.70	19.54	17.11	2.59	16.66	3.04
23	18.10	23.57	20.23	−2.13	19.68	−1.58
	17.80	23.47	20.15	−2.35	19.60	−1.80
	17.40	22.96	19.75	−2.35	19.22	−1.82
	17.70	23.55	20.21	−2.51	19.66	−1.96
24	17.00	20.62	17.94	−0.94	17.46	−0.46
	17.50	20.44	17.80	−0.30	17.33	0.17
	16.50	20.69	18.00	−1.50	17.52	−1.02
	17.10	20.91	18.17	−1.07	17.68	−0.58
25	16.90	20.10	17.54	−0.64	17.08	−0.18
	16.60	20.02	17.48	−0.88	17.02	−0.42
	16.70	19.37	16.98	−0.28	16.53	0.17
	16.90	21.14	18.35	−1.45	17.86	−0.96
26	19.70	19.54	17.11	2.59	16.66	2.04
	19.00	18.84	16.57	2.43	16.13	2.87
	19.00	19.70	17.23	1.77	16.78	2.22
	19.20	20.35	17.73	1.47	17.26	1.94
27	15.90	17.94	15.87	0.03	15.46	0.44
	15.20	17.56	15.58	0.38	15.17	0.03
	15.70	17.49	15.52	0.18	15.12	0.58
	15.60	17.58	15.59	0.01	15.18	0.42
28	14.10	16.91	15.07	−0.97	14.68	−0.58
	14.30	16.47	14.73	−0.43	14.35	−0.05
	13.80	16.44	14.71	−0.91	14.33	−0.53
	14.10	16.51	14.76	−0.66	14.38	−0.28
29	16.70	17.11	15.23	1.47	14.83	1.87
	17.20	16.83	15.01	2.19	14.62	2.58
	18.10	16.92	15.08	3.02	14.69	3.41
	16.90	16.62	14.85	2.05	14.46	2.44
30	13.80	16.14	14.48	−0.68	14.10	−0.30
	13.70	15.92	14.31	−0.61	13.94	−0.24
	13.90	15.58	14.04	−0.14	13.68	−0.22
	14.10	15.71	14.14	−0.04	13.78	0.32
31	14.50	16.75	14.95	−0.45	14.56	−0.06
	14.60	16.60	14.83	−0.23	14.45	0.15
	14.50	16.82	15.00	−0.50	14.62	−0.12
	14.90	16.75	14.95	−0.05	14.56	0.34
32	13.70	15.81	14.22	−0.52	13.86	−0.16
	13.80	15.58	14.04	−0.24	13.68	0.12
	13.80	15.38	13.89	−0.09	13.54	0.26
	16.80	15.22	13.77	3.03	13.42	3.38
33	29.30	33.80	28.14	1.16	27.35	1.95
	29.20	33.79	28.13	1.07	27.34	1.86
	30.70	34.37	28.58	2.12	27.78	2.92
	30.80	34.26	28.50	2.30	27.70	3.10
34	30.50	37.10	30.69	−0.19	29.82	0.68
	30.10	36.45	30.19	−0.09	29.34	0.76
	29.50	36.86	30.51	−1.01	29.64	−0.14
	30.70	37.70	31.16	−0.46	30.28	0.42

a Standard ASTM Method Results

b Moisture Content at 10psi Pressure Intensity

c Plastic Limit as Predicted From The Equation

$$\widehat{PL} = 1.9906 + 0.7737\, WC_{10}$$

d Deviation, Standard Minus Predicted Values

e Plastic Limit as Predicted From The Equation

$$\widehat{PL} = 2.0 + 0.75\, WC_{10}$$

$$LL = -3.5 + 1.50\ WC_{10} \tag{1}$$

$$PL = 2.0 + 0.75\ WC_{10} \tag{2}$$

are compared with the standard LL and PL test results. The deviations of predicted values from observed values, obtained by using the simplified models 1 and 2 are almost the same as the deviations that resulted from using the original models.

Detecting of Non-Plastic and Low Plasticity Soils

This aspect of the study is concerned with the identification of non-plastic* soils by the moisture tension method. The moisture contents (WC_i) of the non-plastic soils were obtained by using four different pressure intensities. Study of the moisture content values indicated WC_i values of the non-plastic soils had an approximate upper-bound limit depending upon the pressure intensity used. Similarly, for the soils exhibiting a plasticity index (PI) less than 3% as well as those with P.I.'s between 3% and 6%, the moisture content (WC_i) values were within specific ranges. These limiting values for various pressure intensities are shown in Table 14.

*Non-plastic soils are defined as those, sandy or non-cohesive soils for which it is difficult or impossible to determine the plastic limit.

Table 14. WC_i Ranges for Non-Plastic and Low Plasticity Soils

Pressure	WC_i Range for Non-Plastic Soils	WC_i Range for Soils with PI < 3%	WC_i Range for Soils with (3% < PI < 6%)
6 psi	<10*	10-15	15-20
10 psi	< 9	9-14	14-19
12 psi	< 8	8-13	13-18
18 psi	< 7	7-12	12-17

*Values are in percent moisture content.

Therefore, it appears that non-plastic soils can be identified by their WC_i values.

Figure 13 shows the relationship of the liquid and plastic limits with the moisture content values WC_i, at various pressure intensities. These relationships can be divided into several distinct segments. The lowest segment "A" indicates the non-plastic region, the region "B" signifies the range from non-plastic to a PI < 3% and region "C" approximates the WC_i values for soils exhibiting PI values between 3 and 6 percent. The region beyond "C" is for soils exhibiting a PI greater than 6 percent.

Reproducibility of Moisture Tension Test Results

The test data obtained from the previous tests on the 38 soil samples using 10 psi pressure intensity were used

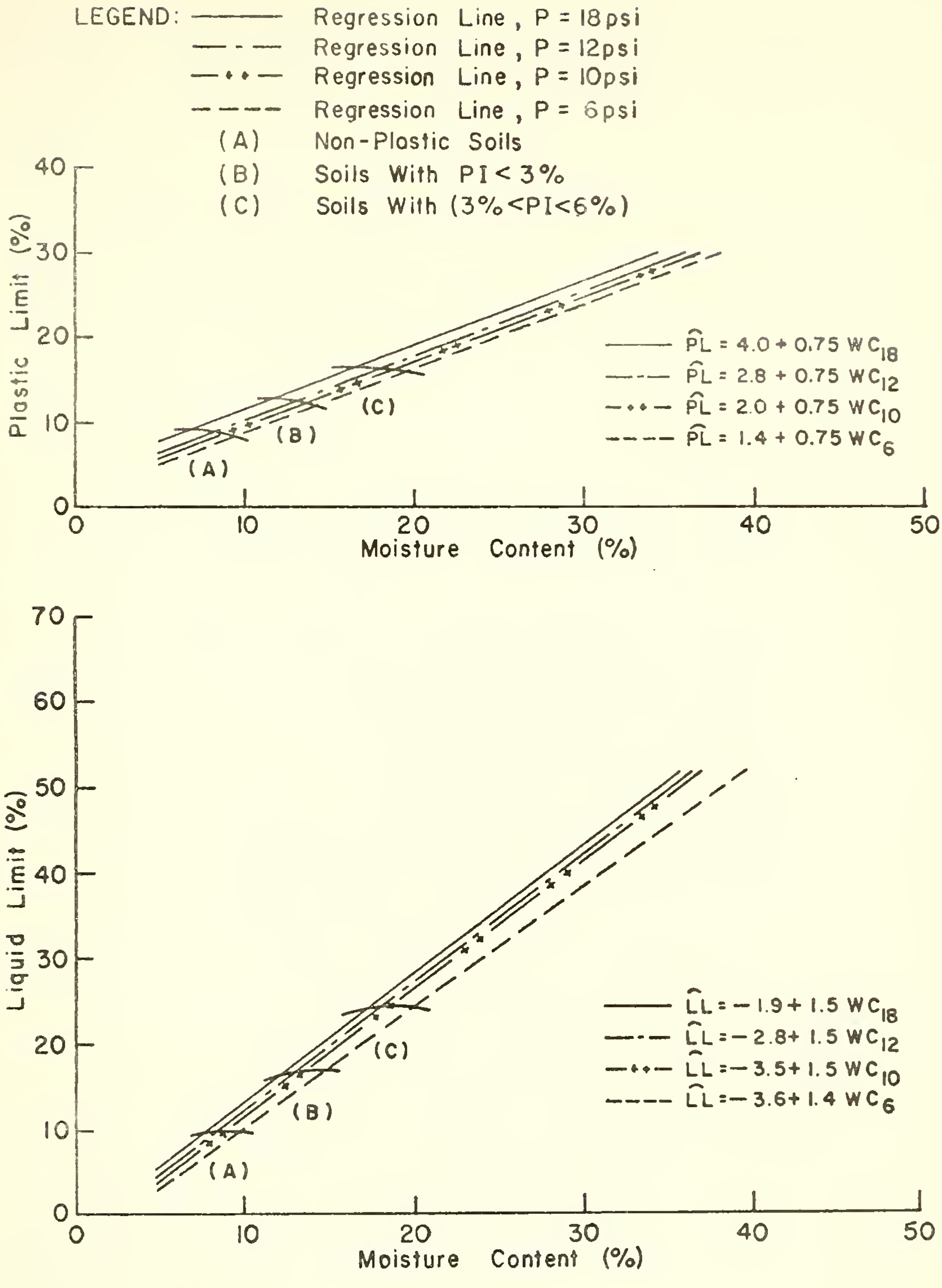

FIGURE 13. Relationship of Liquid and Plastic Limits With The Moisture Content at Various Pressure Intensities

to study the reproducibility of the moisture tension test results. Four replicates were available for each soil type.

Table 15 shows the WC_{10} values along with their mean and standard deviations. The average standard deviation for the replicates from the mean value is approximately 0.33 percent moisture content, the highest is 1.57 percent moisture content.

The analysis of variance was based upon a randomized complete block design using the following model:

$$Y_{ij} = \mu + R_i + \delta_{(i)} + S_j + RS_{ij} + E_{(ij)}$$

where

Y_{ij} = measured variable, moisture content of the soil sample under 10 psi pressure intensity

μ = true mean effect of the population

R_i = true effect of the replicates, $NID(0,\sigma^2{}_R)$

$\delta_{(i)}$ = restriction error, due to blocking effect, $NID(0,\sigma^2{}_\delta)$

S_j = true effect of soil type

RS_{ij} = interaction effect between R_i and S_j

$E_{(ij)}$ = within error, $NID(0,\sigma^2)$.

The subscripts assume the values

$i = 1,2,3,4$

$j = 1,2,\ldots\ldots 38$

The main effect R is random while the main effect S is fixed.

TABLE 15. Moisture Content Values Obtained at 10psi - WC_{10}

SOIL NO.	REPLICATES				MEAN	STANDARD DEVIATION
	1 (%)	2 (%)	3 (%)	4 (%)	(%)	(%)
1	19.25	19.28	19.23	19.05	19.20	0.10
2	19.49	19.31	19.82	19.52	19.54	0.21
3	32.29	32.36	32.33	32.57	32.39	0.13
4	23.34	23.26	23.28	24.66	23.64	0.68
5	16.90	17.01	16.80	16.98	16.92	0.09
6	17.36	17.27	17.55	17.22	17.35	0.15
7	15.22	15.50	14.43	14.98	15.03	0.45
8	16.64	16.60	16.35	16.50	16.52	0.13
9	5.80	6.19	6.10	5.70	5.95	0.23
10	17.92	17.95	18.08	18.19	18.04	0.02
11	5.45	5.66	5.40	5.62	5.53	0.13
12	3.11	3.16	3.20	2.96	3.11	0.11
13	5.97	6.28	5.15	5.71	5.78	0.48
14	32.37	31.88	31.77	31.81	31.96	0.28
15	13.18	13.39	12.04	12.47	12.77	0.63
16	11.30	10.65	11.55	10.32	10.96	0.33
17	27.72	27.23	30.38	29.93	28.82	1.57
18	26.93	26.49	26.13	25.97	26.38	0.43
19	28.10	29.02	27.74	28.13	28.25	0.55
20	23.21	22.97	23.66	24.16	23.50	0 53
21	20.02	19.92	19.02	19.33	19.57	0.48
22	20.20	19.44	19.80	19.54	19.75	0.34
23	23.57	23.47	22.96	23.55	23.39	0.29
24	20.62	20.44	20.69	20.91	20.67	0.19
25	20.10	20.02	19.37	21.14	20.16	0.73

TABLE 15 , Cont.

SOIL NO.	REPLICATES 1 (%)	2 (%)	3 (%)	4 (%)	MEAN (%)	STANDARD DEVIATION (%)
26	19.54	18.84	19.70	20.35	19.61	0.62
27	17.94	17.56	17.49	17.58	17.64	0.20
28	16.91	16.47	16.44	16.51	16.58	0.22
29	17.11	16.83	16.92	16.62	16.87	0.20
30	16.14	15.92	15.58	15.71	15.84	0.25
31	16.75	16.60	16.82	16.75	16.73	0.09
32	15.81	15.58	15.38	15.22	15.50	0.26
33	33.80	33.79	34.37	34.26	34.06	0.30
34	37.10	36.45	36.86	37.70	37.03	0.52
35	13.75	13.95	13.84	14.02	13.89	0.12
36	3.40	3.24	3.20	3.36	3.30	0.09
37	14.50	14.30	14.15	14.40	14.34	0.15
38	12.85	13.10	12.79	13.00	12.94	0.14
AVERAGE STANDARD DEVIATION						0.33

Table 16 summarizes the analysis of variance. In this model it was assumed that $\sigma^2_{RS} = 0$, so that the mean square attributed to the interaction source (RS), could be used as the error estimate. From the ANOVA the effect of the replicates on the test results turns to be not significant using $\alpha = 0.25$. This means that the hypothesis of non-significance of the effect of replicates may be accepted.

From the previous results it is concluded that the moisture tension method results (WC_i) are independent of the effect of repeat measurements. In other words, the moisture tension method has a high degree of reproducibility.

Time Factor Study

The moisture content WC_i, obtained by the moisture tension method is a function of the loading time. As the loading time increases the moisture content WC_i decreases, until an equilibrium state is attained after which the change of WC_i with time becomes negligible.

Figure 14 through 16 show the relationship between the moisture content, WC_i, and the loading time for the five soils used in this study. The moisture content, WC_i, values are the average of two measurements. Pressure intensities of 10 and 18 psi were used to study this relationship.

TABLE 16. Summary of Analysis of Variance – WC_{10}

SOURCE OF VARIATION		DEGREE OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-STATISTIC	F-0.25	SIGNIFICANCE
REPLICATION	R_i	3	0.72	0.24	1.26	1.40	NS
RESTRICTION ERROR	$\delta_{(i)}$	0					
SOIL TYPE	S_j	37	9886.72	267.21			
INTERACTION	RS_{ij}	111	20.92	0.19			
ERROR	$E_{(ij)}$	0					
TOTAL		151	9908.36				

MODEL: $Y_{ij} = \mu + R_i + \delta_{(i)} + S_j + RS_{ij} + E_{(ij)}$

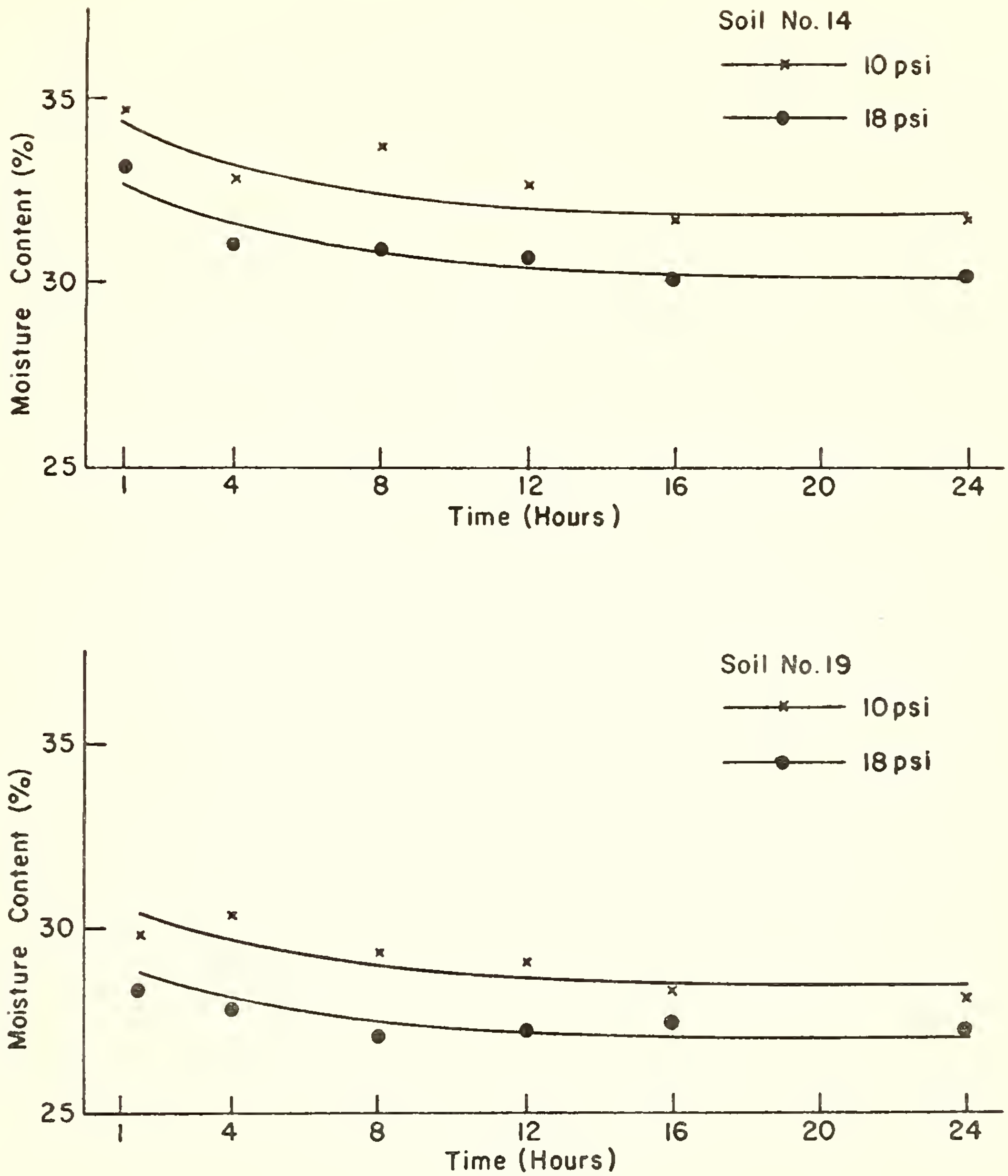

FIGURE 14. Effect of Time on The Moisture Content — Soils No. 19 and 14
(Moisture Content Values are the Average of Two Tests)

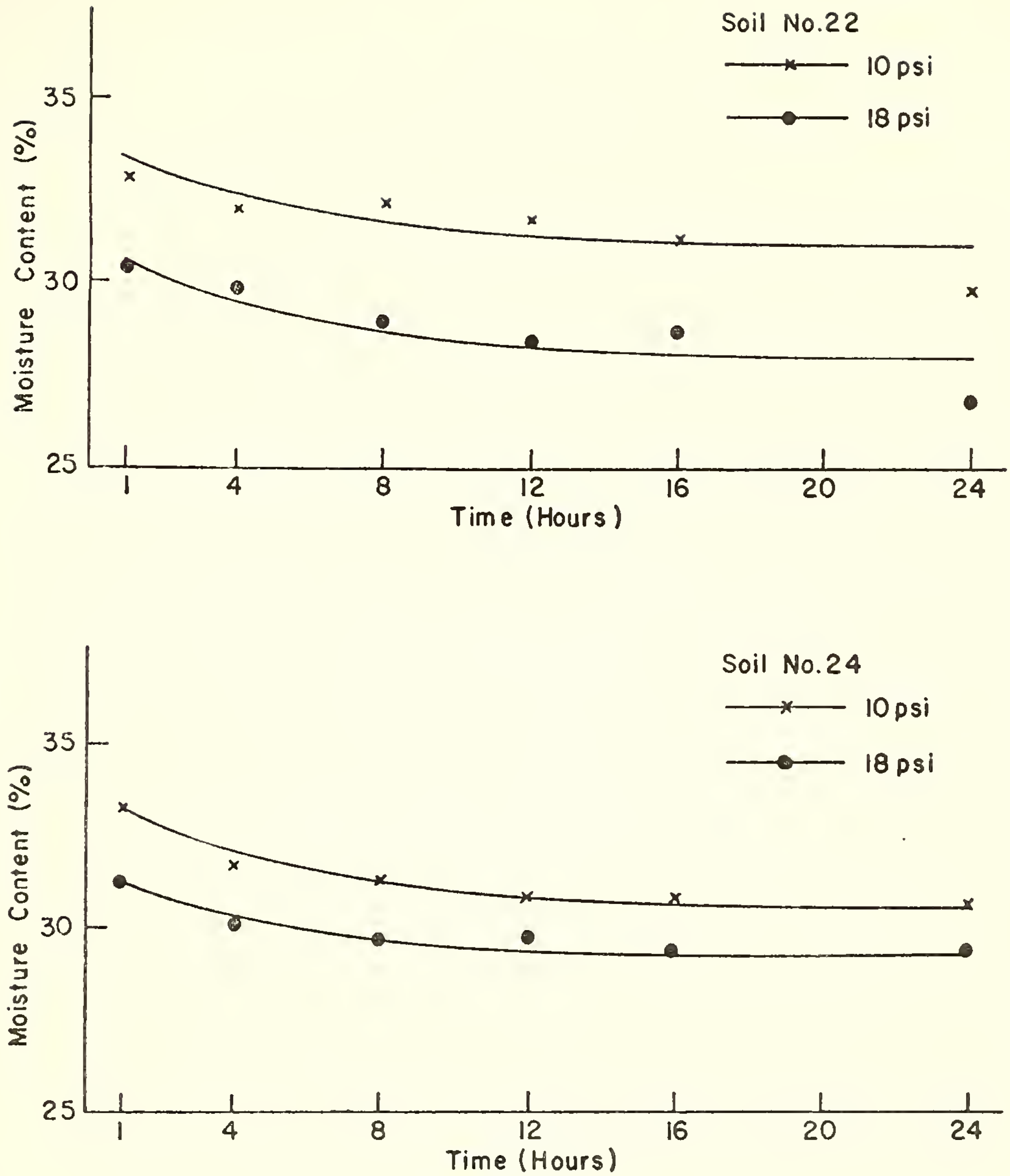

FIGURE 15. Effect of Time on The Moisture Content — Soils No. 22 and 24
(Moisture Content Values are the Average of Two Tests)

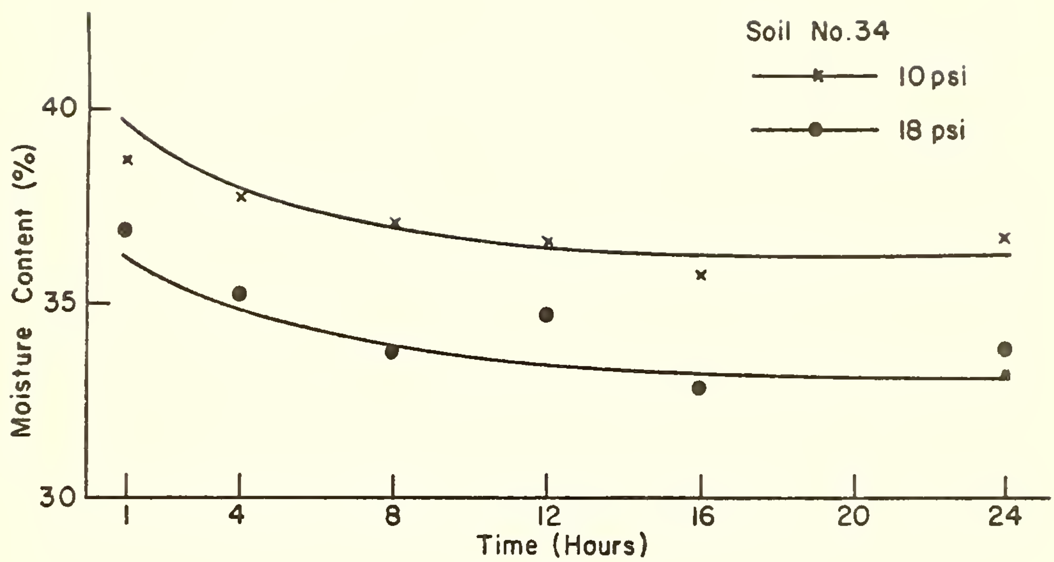

FIGURE 16. Effect of Time on The Moisture Content — Soil No. 34
(Moisture Content Values are the Average of Two Tests)

The test data were examined statistically in two parts. The first step was to perform an analysis of variance to obtain an estimate of error. This information was needed for a comparison test (Newman-Keuls test) on the time factor treatment means.

The analysis of variance was based upon a randomized complete block design (RCBD), using the following linear model:

$$Y_{ijk} = \mu + R_i + \delta_{(i)} + T_j + RT_{ij} + W_{(ij)} + S_k +$$

$$RS_{ik} + TS_{jk} + RTS_{ijk} + E_{(ijk)}$$

where

Y_{ijk} = the measured variable, moisture content of the soil samples

R_i = true effect of the replicates, $NID(0,\sigma^2_R)$

T_j = true effect of the time factor

S_k = true effect of the soil type

$\delta_{(i)}$ = first restriction error, zero df, $NID(0,\sigma^2_\delta)$

$W_{(ij)}$ = second restriction error, zero df, $NID(0,\sigma^2_W)$

$E_{(ijk)}$ = true random error, zero df, $NID(0,\sigma^2)$

The other terms denote the interaction among the factors R, T and S. The subscripts assume the values:

$i = 1,2$

$j = 1,2,3,4,5,6$

$k = 1,2,3,4,5$

In the ANOVA model, the main effects T and S are fixed while R is random.

This type of experimental design has been described in detail in a preceding section of this thesis. The analysis of variance results are not shown as this analysis was performed primarily to obtain an estimate of error for the Newman-Keuls sequential range test.

Newman-Keuls sequential range test was conducted to perform a comparison test on the time factor treatment means. Tables 17 and 18 show Newman-Keuls test results for two test conditions of 10 psi and 18 psi pressure intensities respectively.

The results of the analysis indicate:

1. Using 10 psi pressure intensity, the WC_i values obtained after a loading time of 16 hours are not significantly different from the WC_i values obtained after a loading time of 24 hours.
2. Using 18 psi pressure intensity, the WC_i values obtained after a loading time of 8 hours are not significantly different from those obtained after 12 hours or greater.

A limitation of the above conclusions must be borne in mind. The soils used for the tests to study the effect of time factor, had a maximum plasticity index of about 20. Consequently, these conclusions may not hold for soils having high plasticity indices (e.g., high plastic clays)

TABLE 17. Newman-Keuls Sequential Range Test For The Time Factor Study (Pressure Intensity 10psi)

Error Mean Square = 0.0675 (Obtained From ANOVA)

Degree of Freedom = 25

No. of Observations Per Treatment = 10

LOADING TIME IN HOURS	RANK OF MEANS	MEANS
1	1	29.88
4	2	28.97
8	3	28.71
12	4	28.17
16	5	27.58
24	6	27.45

Tests of Differences Between The Means

RANK	6	5	4	3	2
1	2.43**	2.30**	1.71**	1.18**	0.91**
2	1.52**	1.39**	0.80**	0.26*	
3	1.26**	1.13**	0.54**		
4	0.72**	0.59**			
5	0.13				

* Significant at α = 0.05

** Significant at α = 0.01

TABLE 18 .Newman-Keuls Sequential Range Test For The Time Factor Study (Pressure Intensity 18psi)

Error Mean Square = 0.2752 (Obtained From ANOVA)

Degree of Freedom = 25

No. of Observations Per Treatment = 10

LOADING TIME IN HOURS	RANK OF MEANS	MEANS
1	1	27.99
4	2	27.04
8	3	26.05
12	4	25.97
16	5	25.62
24	6	25.41

Tests of Differences Between The Means

RANK	6	5	4	3	2
1	2.58**	2.37**	2.02**	1.94**	0.95**
2	1.63**	1.42**	1.07**	0.99**	
3	0.64	0.43	0.08		
4	0.56	0.35			
5	0.21				

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

which may require relatively longer times to attain the equilibrium state.

Verification of the Proposed Mathematical Models

To verify the proposed relationships, additional soil samples with previously determined test values were obtained from a highway commission laboratory outside Indiana. A total of 144 samples were selected in a randomized manner representing a large range in soil texture. The liquid limits of these samples ranged between 15 and 80 percent moisture content; the highest plasticity index was 60 percent moisture content. The moisture tension method test was run on these samples at a pressure intensity of 10 psi.

Liquid Limit Relationships

The liquid limit prediction model,

$$LL = -3.50 + 1.50\ WC_{10} \qquad (1)$$

was applied to the check samples data. The coefficient of determination, R^2, resulting from applying model No. 1 to the check samples data was 0.89. A plot of standard LL values vs. WC_{10} for the check samples together with model No. 1 are shown in Figure 17. The deviations of the predicted values from the standard values using model No. 1 are summarized in Table 19.

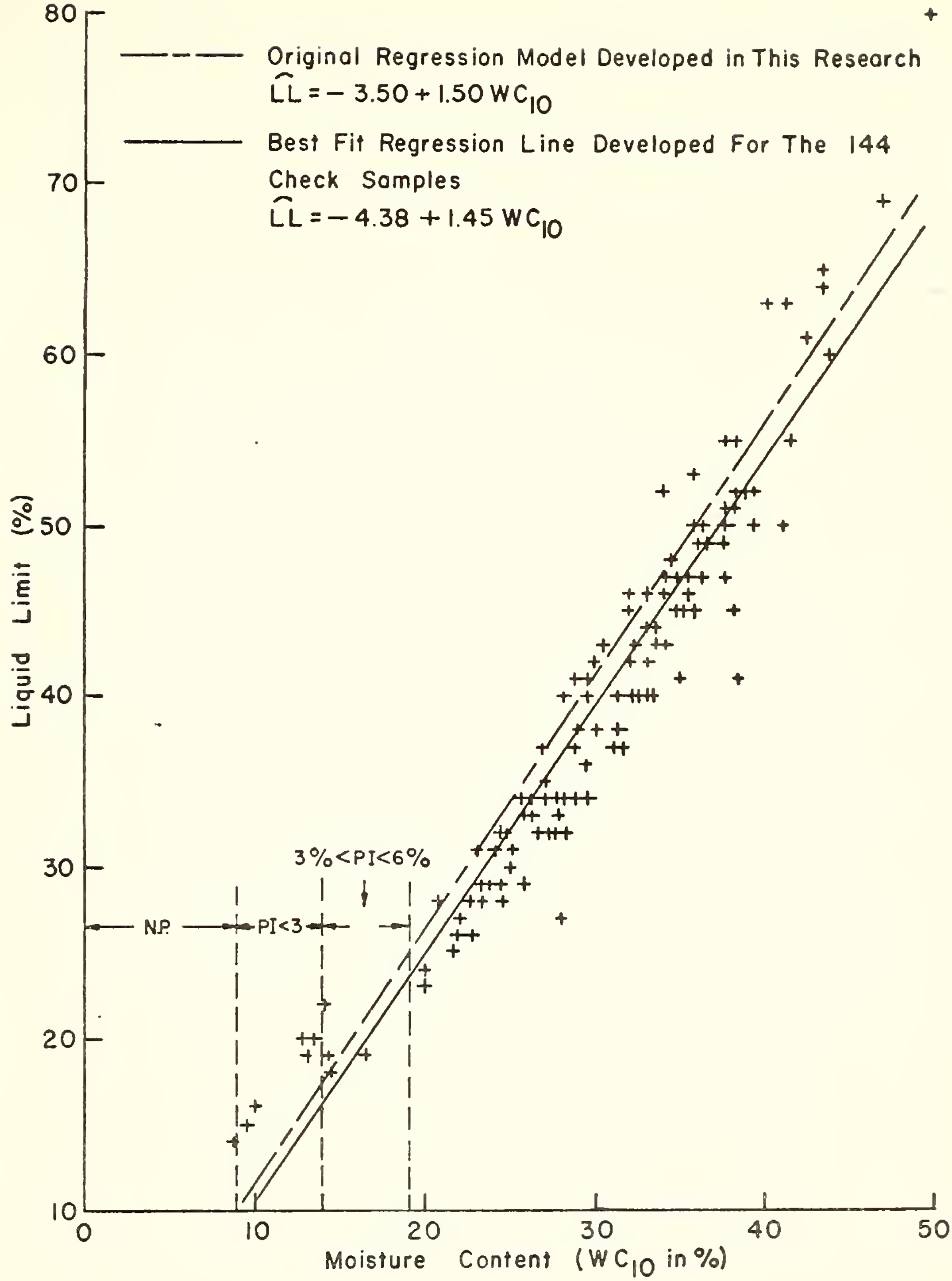

FIGURE 17. Relationship Between The Liquid Limit and Moisture Content at 10psi For The Check Samples (144 data points)

In order to investigate the possibility of a better fitting model for the check samples, a regression analysis was made. The analysis resulted in the following linear model with a coefficient of determination, $R^2 = 0.92$.

$$LL = -4.38 + 1.45\ WC_{10} \qquad (2)$$

A plot of this model is shown in Figure 17 . The deviations of the predicted values from the standard values using model No. 2 are summarized in Table 19.

Table 19. Summary of Deviation of Predicted LL Values From the Standard Values

Deviation[a]	Model No. 1[b] No. of Samples		Model No. 2[c] No. of Samples	
1-2	65	(45.2%)[d]	87	(60.5%)
3-4	42	(29.2%)	36	(25%)
>4	37	(25.6%)	21	(14.5%)

[a]Standard LL minus predicted LL in percent moisture content

[b]Using the model: $LL = -3.50 + 1.50\ WC_{10}$

[c]Using the model: $LL = -4.38 + 1.45\ WC_{10}$

[d]Values in parentheses are percent of data falling within a given range of deviation

It is observed that model No. 2 results in smaller deviations from the standard LL values for the check data as compared with model No. 1.

The next step in this analysis was to statistically compare models 1 and 2. Both models have a general form of the type:

$$LL = b_0 + b_1 \, WC_{10} \tag{3}$$

Ninety-five percent confidence limits on the intercept b_0 in model No. 1 resulted as:

$$-5.10 < B_0 < -1.98$$

Similarly the 95% confidence limits of the slope b_1 of model No. 1 resulted as: $1.42 < B_1 < 1.55$

It is seen that the slope b_1 of model No. 2 lies within the confidence limits for B_1 shown above. This was true for the intercept b_0 of model No. 2.

The difference in the intercept values may be attributed to the fact that model No. 1 was developed using the LL data obtained by a single operator at Purdue University Pavement Design Laboratory, whereas model No. 2 was based on LL data obtained by several operators. Hence, the shift in intercept values is attributed primarily to operator variability. In any case it may be inferred from this analysis that a linear model is perhaps the best fit to define the LL vs WC_{10} relationship.

The high coefficient of determination for model No. 1 was obtained by using 144 check samples. Some of the data points were found to lie outside the inference space

of the postulated prediction model. This indicates that the LL prediction model is even valid for data lying outside its inference space.

Plastic Limit Relationships

A plot of standard PL vs. WC_{10} data for the check samples is shown in Figure 18. It is obvious that a linear model is a poor fit for the check sample data. A correlation analysis of PL and WC_{10} for the check samples resulted in a simple correlation coefficient, $r = 0.63$.

During the development of the plastic limit prediction model, it was suggested that the model be only used for prediction of plastic limits of soils having a PI < 21 percent and a LL < 50 percent. This constitutes the inference space of the model. Some of the check sample data lie outside the inference space indicated above. In order to satisfy the limitations of the prediction model, only the data lying inside the prescribed range were included for the analysis (91 data points). The plastic limit prediction model,

$$PL = 2.0 + 0.75\ WC_{10} \tag{4}$$

the best fitting linear regression model,

$$PL = 4.77 + 0.54\ WC_{10} \tag{5}$$

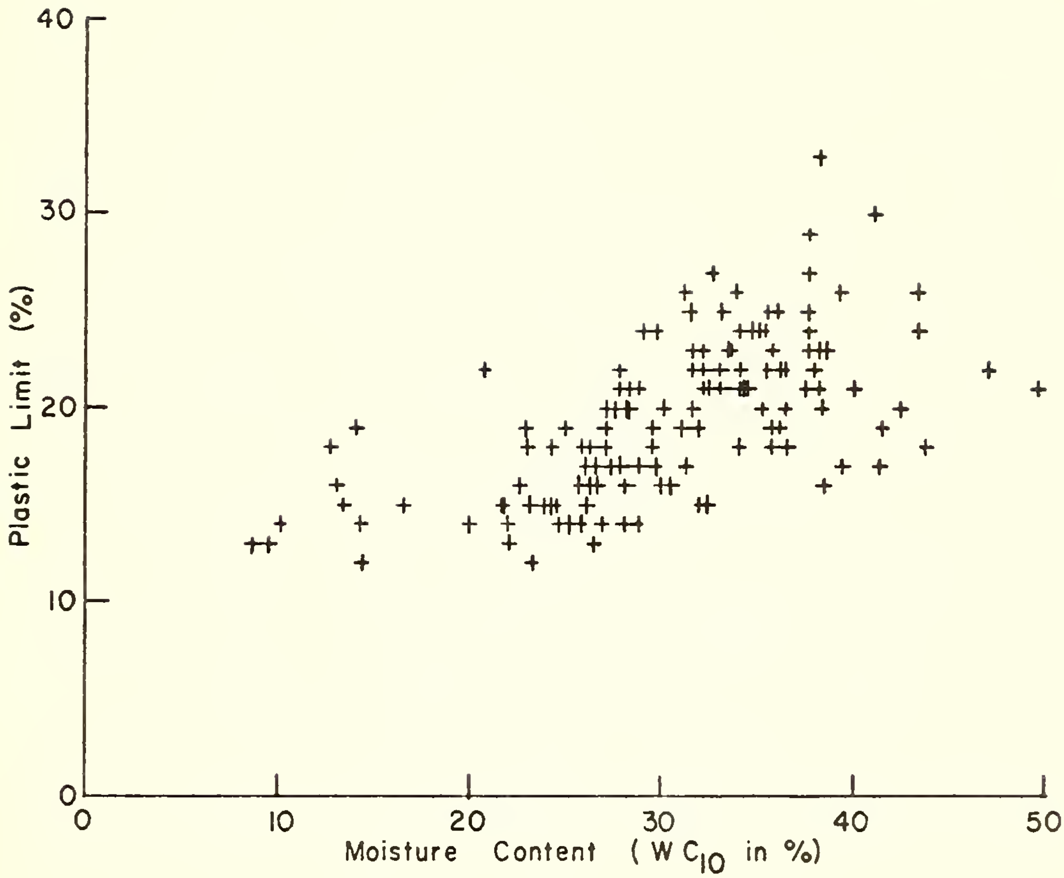

FIGURE 18. Relationship Between The Plastic Limit and Moisture Content at 10psi For The Check Samples (144 data points)

and the reduced data (91 data points) are shown in Figure 19. Model No. 5 resulted in a coefficient of determination, $R^2 = 0.60$. The simple correlation coefficient, r, between PL and WC_{10} for the reduced data increased to 0.78

The deviation of predicted values, using both models 4 and 5 from the standard plastic limits are summarized in Table 20.

Table 20. Summary of Deviation of Predicted PL Values from the Standard Values

Deviation[a]	Model No. 4[b]		Model No. 5[c]	
	No. of Samples		No. of Samples	
1-2	19	(21%)[d]	57	(62.5%)
3-4	27	(29.5%)	29	(32%)
> 4	45	(49.5%)	5	(5.5%)

[a]Standard PL minus predicted PL in percent moisture content.

[b]Using the model: $PL = 2.0 + 0.75\ WC_{10}$.

[c]Using the model: $PL = 4.77 + 0.54\ WC_{10}$.

[d]Values in parentheses are percent of data falling within a given range of deviation.

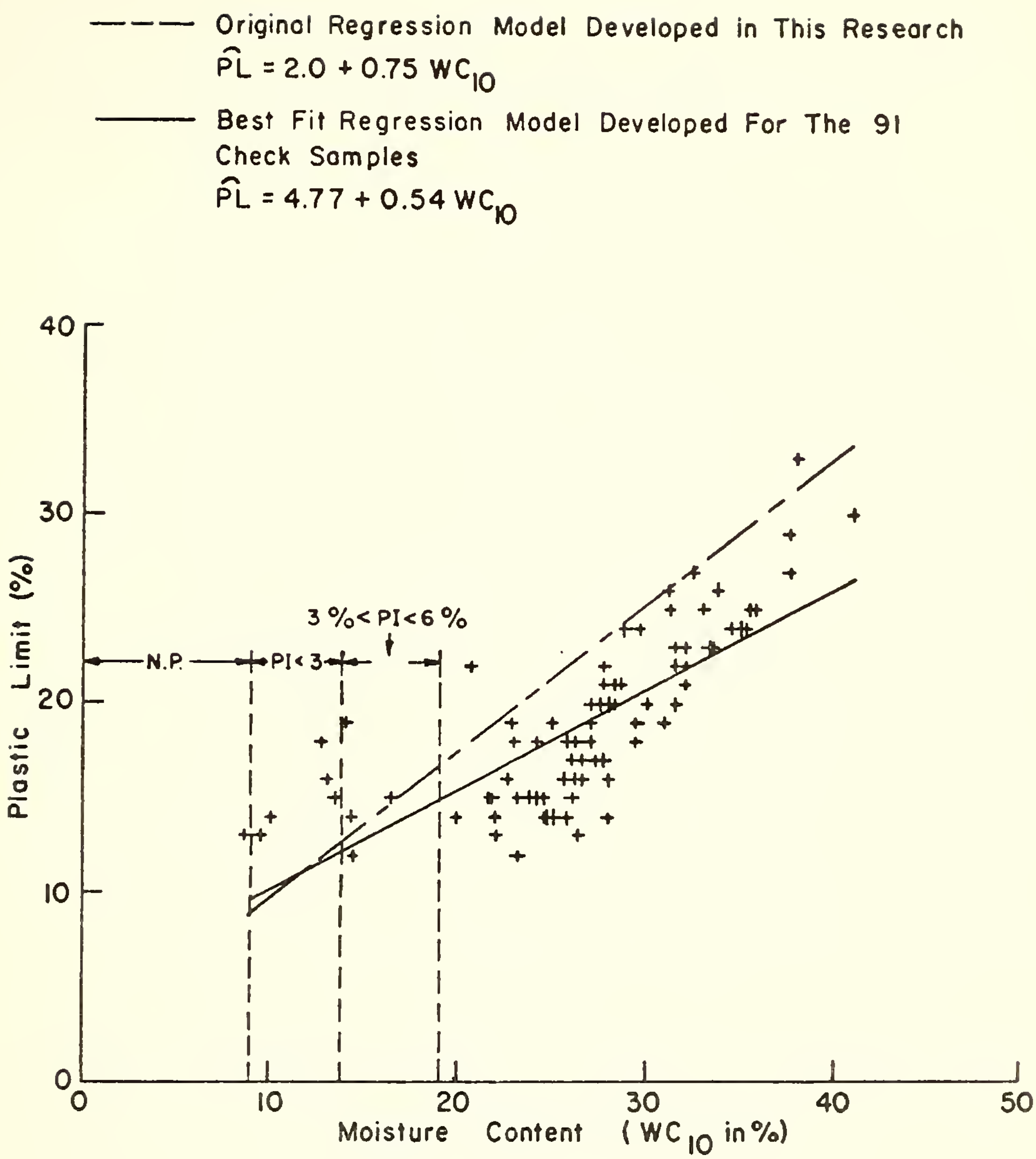

FIGURE 19. Relationship Between The Plastic Limit and Moisture Content at 10 psi For The Check Samples (91 data points)

Though the coefficient of determination of the best-fitting linear regression of model No. 5 is generally low, it is observed that the error resulting from the use of this model for the plastic limit is compatible with the reproducibility criteria for standard PL values.

Non-Plastic and Low Plasticity Soils

It was observed that the ranges of WC_{10} values postulated for non-plastic and low plasticity soils are valid for the check sample data. These ranges are indicated in Figures 17 and 19.

Interpretation of the Analysis for the Verification of the Prediction Models

The liquid limit prediction model showed good agreement with the best-fitting linear regression model for the check samples data. A linear relationship for these parameters explains 92% of the variation in the data.

The plastic limit model resulted relatively poor prediction of the plastic limit values of the check samples. The analysis to determine the best-fitting linear model for the check sample data resulted in an R^2 value of 0.60. This low value can possibly be explained by the fact that forces other than capillarity affect the moisture tension test results, especially in the case of clays. Baver (3) suggested that the water holding capacity of soils is a function of the clay content, the

type of clay minerals, amount of organic matter and porosity. It is possible that different mineralogical characteristics and origin of the check soils may have caused the differences observed during the verification of these models. Further, some of the difference can be attributed, to the operator variability.

The ranges of WC_{10} values suggested previously for non-plastic soils as well as those with low plasticity remained the same for the check sample data as for the original data (see Figures 17 and 19).

CONCLUSIONS

All conclusions stated herein are limited to the materials and tests used in this study. The results of this study may be summarized as follows.

1. Within the range of procedures studied herein the method of preparation of soil samples did not significantly influence the moisture tension test results. However, the interaction between the soil type and method of preparation was significant. This suggests that for some soil types the method of preparation may have an effect on the test results. To circumvent this possibility, it is suggested that a standardized method of preparation of soil samples be used. This method is that designated as Method No. 4 in this thesis.

2. Linear relationships were developed between the consistency limits (LL and PL) and the moisture content, WC_i, obtained at 6, 10, 12 and 18 psi pressure intensity. These relationships offer the possibility of using linear models, correlating the consistency limits with the

moisture content, WC_i, for predicting liquid and plastic limits.

3. The results of the verification of the consistency limits-WC_{10} relationships indicated that:

   a) The proposed liquid limit prediction model may be used with confidence for the prediction of liquid limit values by using the moisture tension test method at a pressure intensity of 10 psi.

   b) Though some linearity exists between the plastic limit and WC_{10} data obtained by using the check samples, the correlation was relatively low ($r = 0.78$). This suggests that forces acting during the moisture tension test are extremely complex. This conclusion should be carefully considered since the soil samples used for checking the proposed models were obtained from a different geographical location and may not be, as such, negate the validity of the PL-WC_{10} relationship.

4. The non-plastic and low plasticity soils can be identified by their WC_i values, as obtained by the moisture tension method.

5. The results of replicate tests showed that the standard plastic limit tests were relatively more reproducible than the standard liquid test. Contrarily, the moisture tension method shows a high degree of reproducibility at all times. The high degree of reproducibility of the moisture tension test lends emphasis to its potential utility as a routine test.
6. The time factor study indicated that, using a pressure intensity of 10 psi, the loading time of 16 hours gave WC_{10} values not significantly different from those obtained after 24 hours. Further, for 18 psi pressure intensity a loading time of 8 hours was enough to obtain WC_{18} values that were not significantly different from the values obtained after 24 hours .

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